Polarization lidar at 1.54 μm and observations of plumes from aerosol generators

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Abstract. The ability to detect relative changes in backscatter polarization from a scanning high-pulse-energy lidar system at 1.54-μm wavelength is demonstrated. The new capability was tested during the dissemination of various biological aerosol simulants and other particulate emissions at the U.S. Army’s Dugway Proving Ground. Results demonstrate that the lidar is sensitive to different types of aerosols, and departures from the atmospheric background depolarization ratio are consistent with the limited amount of information available on the degree of particle sphericity. We conclude that the polarization-sensitive coatings of the beam-steering unit mirrors are presently the largest source of error and that this error is minimized when scanning with a near-zero elevation angle. This is an encouraging result for aerosol source surveillance applications, where the depolarization information may be useful in determining the aerosol generation mechanism or provide an additional scalar variable for use in delineating the plume from the background. © 2007 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.2786406]

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1 Introduction

The polarization lidar technique has frequently been used to study the thermodynamic (microphysical) phase of naturally occurring water clouds. For example, clouds composed of droplets (liquid spheres) exhibit low backscatter depolarization, while clouds composed of crystals (ice) exhibit high depolarization. The technique has also been applied to distinguish elevated aerosol layers. A very limited amount of work has been published on applying this technique to biological aerosol plumes. Yee et al. present results from a 1.06-μm-wavelength lidar and a single type of biological aerosol simulant from a range of 100 m. Lee et al. present results from a variety of simulants using a 523-nm-wavelength micropulse lidar. In this work, we apply the polarization technique to a unique, high-pulse-energy, 1.5-μm-wavelength, direct analog-detection lidar and demonstrate its ability to detect significant differences in the linear depolarization ratio of airborne particles that make up relatively small, near-ground aerosol plumes at horizontal ranges of several kilometers. We expect this capability to be valuable in both atmospheric research and standoff detection. For example, aerosol plumes exhibiting low depolarization ratios are likely to be composed of spherical particles, while plumes exhibiting high depolarization ratio are likely to be composed of nonspherical material. Although the depolarization ratio does not indicate the composition of material, it may indicate the likely mechanism of generation and assist in the delineation of the plume from the background.

The Raman-shifted Eye-safe Aerosol Lidar (REAL) at the National Center for Atmospheric Research (NCAR) was designed to be a field-deployable atmospheric research instrument—capable of rapidly revealing the structure of the clear atmosphere via optical aerosol scattering. Eye safety at all ranges, rapid scanning, and long-range operation were the primary design goals. Therefore, the system was designed to operate at 1.5-μm wavelength. The details of the design and development of this system are covered in previous papers. In this paper, we report on how the system was upgraded to enable depolarization measurements and show results from deployment of the system in the field.

2 System Upgrades

The system diagram shown in Fig. 1 shows the arrangement of major hardware components for the field data presented herein. To implement backscatter depolarization capability on REAL, the polarization purity of the pump beam was improved by placing an optical isolator near the exit of the Nd:YAG laser. The optical isolator consists of a Faraday rotator and two polarizers; each polarizer is a pair of double dielectric Brewster plates each with an extinction ratio of 10^-4. Here, the extinction ratio is defined as the transmittance  T_p perpendicul a r to the plane of polarization divided by the transmittance  T_0 parallel to the plane of polarization, or  T_p/T_0. In addition to improving the polarization purity, the isolator protects the pump laser from poten-
cial optical feedback. However, it reduces the available pump energy by about 20% to about 615 mJ per pulse.

2.1 Frequency Conversion: Raman Cell

Within the last three years, NCAR has designed, constructed, and operated two new generations of Raman cells that overcome traditional problems. The first-generation Raman cell [see Fig. 2(a)] employed entrance and exit windows, and internal mirrors, that were within a few degrees of perpendicular to the beam. Despite the great improvement over traditional cells, this design still had some disadvantages. First, the windows required antireflection (AR) coating to prevent losses each time beam passes through. Second, the internal mirrors are parallel, and therefore the beam path is slightly overlapped with itself in front of each mirror. These doubly illuminated volumes can potentially degrade the beam quality. The AR and high reflection (HR) coatings can be problematic for two reasons. First, unavoidable manufacturing defects in the coatings can result in burning of the coating in the presence of a high-energy laser beam. Second, even with a good coating, slow photochemical etching occurs on the interior sides of the windows due to the interaction of the coating material with methane in the presence of the intense IR light. This effect is very slow, but it was fast enough that we replaced the windows with uncoated substrates on one side (the interior side) within a year.

A second-generation Raman cell [see Fig. 2(b)] that eliminates the problems of the first-generation cell and provides better performance was designed, fabricated, and tested. The second-generation cell employs all uncoated optics with surfaces at the Brewster angle. In this design, prisms are used to fold the beam within the cell. In addition to eliminating the vulnerable AR and HR coatings, this design eliminates the beam overlap regions. The second-generation cell also includes improved internal shrouding and flow straighteners so the gas flows transverse to the beam plane with reduced turbulence. The frequency converter is robust and capable of high conversion efficiency (>36%). Pumping with 615 mJ/pulse at 10 Hz results in 1.5-μm pulse energies in excess of 225 mJ with a beam quality parameter $M^2$ of less than 8. The beam quality is critically important to ensure the transmitted beam has a divergence less than the angle corresponding to the receiver’s field of view. Currently, it is most practical to use InGaAs avalanche photodiodes (APDs) as detectors for lidars at this wavelength. The maximum active area of this type of detector is 200 μm in diameter. This small detector therefore subtends a very narrow field of view and places a requirement of low divergence on the transmit beam.

2.2 Receiver Optics

To separate the polarization components of the backscattered light, a 25-mm-clear-aperture calcite air-gap Glan-Taylor polarization beamsplitter cube was integrated into the receiver. Figure 3 shows a ray trace of the receiver from the focal plane of the telescope to the two photodetectors. This portion of the instrument is completely contained within a 30×35×19-cm enclosure to shield it from any scattered light from the nearby transmitter. The first element of this assembly is a lens designed to collimate the light for transmission through the subsequent optics. These include a neutral density (ND) filter, an interference filter, a half-wave plate, and the polarization beamsplitter cube. The ND filter is part of a filter wheel that allows the backscatter signal to be attenuated to prevent saturation and reduce the
risk of damaging the photodetectors with hard-target reflections. The filter wheel has six settings: 0, 0.5, 1.0, 1.5, 2.0, and 2.5. These correspond to transmissions of 100%, 31.6%, 10.0%, 3.16%, 1.0%, and 0.316%, respectively. We confirmed these values experimentally by holding the beam stationary, collecting approximately 1 min of data with each ND filter setting, and then comparing the average backscatter intensity for each setting. The half-wave plate, installed in a rotary mount, is used to rotate the backscattered light and line it up with the axis of the polarization beamsplitter. In addition, the plate can be oriented to split the signal equally, or switch to either channel during calibration to verify that the detector amplifier gains match.

If linearly polarized light is transmitted and the backscattered light is returned from the atmosphere in the same polarization plane, it passes through the cube and is focused on the InGaAs APD on the right side of the diagram referred to as the parallel channel. The beamsplitter cube has an extinction ratio of $10^{-6}$ for this transmitted beam. In the case of depolarized returns, the orthogonal polarization component to the transmitted plane is reflected out the side of the beamsplitter cube at an angle of 109.9° to the axis of the parallel beam. This light is focused on to a second InGaAs APD at the center and bottom of the diagram referred to as the perpendicular channel. Note that 3% of the parallel polarized light is also reflected, albeit at a slightly different angle exiting the cube. However, the difference in angle is sufficiently large to provide good separation. Given the fast-focusing lens and small detector diameter, only 0.3% of the reflected parallel-polarized light falls within the detector active area. Therefore, the linear depolarization ratio (calculated by dividing the perpendicular-channel by the parallel-channel intensity) can be measured with a precision of $10^{-4}$, ultimately limited by the signal-to-noise ratio.

### 2.3 Receiver Electronics

Several improvements were made to the detector-amplifier modules described by Spuler and Mayor. Figure 4 shows a simplified schematic of the new detector-amplifier module. The module now uses a Perkin-Elmer C30659-1550-R2A InGaAs APD. This off-the-shelf component features an avalanche photodiode coupled with a preamplifier in a single device. The diameter of the active element is 200 μm. The module provides the ability to adjust the bias of the photodiode to compensate for gain changes that result from temperature variations. Photodiode bias stabilization is performed via a custom Labview program that reads a digitized voltage from the temperature-sensing diode contained in the C30659-1550-R2A package. The program computes a running 10-s mean of the temperature and ad-

![Fig. 2 Laser beam path through two generations of Raman cells. (a) The first generation used windows and mirrors with anti-reflection and high-reflection coatings, respectively. (b) The second generation uses optics with surfaces at the Brewster angle and prisms for total internal reflection. Therefore, no coatings are necessary.](Figures/2.png)
justs the bias of the detector using the temperature-versus-gain relationship provided by the APD manufacturer.

The InGaAs APD is combined with a postamplifier stage and additional support circuitry on a custom-printed circuit board. The postamplifier stage is employed in order to (1) provide additional gain, (2) provide adjustability of the voltage offset to fall within the input range of the digitizer, (3) drive a 50-Ω coaxial cable (to allow a large distance between the amplifier and the data acquisition computer), (4) provide adjustable gain so that the same optical power from the two modules yields the same voltage, and (5) compensate for the considerable voltage offset of the APD. The postamplifier is an AD829 high-speed, low-noise, operational amplifier (op-amp) operating in an inverting configuration; amplifier gain and offset can be adjusted using two trimpots.

An additional source of error in the depolarization-ratio measurement results from any mismatches in the bandwidths of the detector-amplifier modules. This error would evidence itself near sharp aerosol gradients. To determine the bandwidth of the detector amplifier modules, we created optical pulses in our laboratory by the following

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**Fig. 3** Ray trace of the receiver from the focal plane of the telescope to the two detectors. Numbered components and locations are as follows: 1, focal plane of telescope; 2, collimation lens; 3, neutral-density filter; 4, interference filter; 5, half-wave plate; 6, polarization beamsplitter cube; 7, focusing lens triplet; 8, parallel-channel focal plane; 9, perpendicular-channel focal plane.

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**Fig. 5** Schematic of the Standoff Ambient Breeze Tunnel (sABT) for June 10, 2005, measurements of aerosol depolarization ratios. Not to scale.
method. An electronic pulse generator was used to drive an electro-optic modulator (EOM). The square pulse was about 100 ns in duration with rise and fall times on the order of 1 ns. Next, a continuous wave (cw) laser beam was passed through the EOM, thereby modulating the beam with the same pulse characteristics. Finally, the modulated laser beam was directed onto the active area of our detector module, and the rise and fall times from the signal were recorded. The 3-dB frequency bandwidth was estimated by dividing the 10%-to-90% rise time by 0.35. Results of these tests indicate that the detector and amplifier bandwidths were 3.8 and 4.4 MHz, respectively. These bandwidths are approximately one order magnitude lower than our original expectations, which were based on using the small-signal bandwidth in the AD829 amplifier data sheet as an estimate of achievable device bandwidth. This assumption is not valid for many lidar data cases and certainly not for the strong backscatter gradients encountered in the tests described in this paper. Since the field tests described herein, we have improved the bandwidth to \( \geq 12 \) MHz by modifying the postamplifier electronics. Analog signals from the parallel and perpendicular detector-amplifier modules are digitized at 50 Msample/s and 14-bit quantization.

3 Field Results

3.1 Standoff Ambient Breeze Tunnel

In this section we show depolarization ratios for different types of aerosols released inside Dugway Proving Ground’s Standoff Ambient Breeze Tunnel (sABT). The REAL was located 930 m from the southern entrance of the tunnel. The sABT is a long, narrow, open-ended structure (approximately 120 m long by 5 m diameter), designed to allow a lidar beam to pass through while simultaneously releasing particulate matter inside the tunnel. This is accomplished by use of a large fan and (HEPA) filter installed in a small building connected to, and open to, one side of the tunnel. As shown in Fig. 5, the fan draws air from the tunnel and pushes it through the HEPA filter to remove any particulate matter. Outdoor air is drawn into both ends of the tunnel. Aerosol generators are located at the northern end of the tunnel, and the concentrations of simulants inside the tunnel are controlled by dissemination rate of the aerosol generators. Aerodynamic particle sizer (APS) units were placed on the floor at approximately 12-m intervals to monitor the particle size distribution and concentration in the tunnel as a function of time. During operation the flow through the tunnel is typically a few meters per second and sufficiently turbulent to mix the particles homogeneously from the floor to the ceiling.

The distance from the side opening, at approximately 965 m from the lidar, to the far end of the tunnel at about 1050 m, is referred to as the sample volume. The lidar beam was directed into the tunnel and checked for position by walking the length of the tunnel with an IR viewing camera and a cork board. The direction of the beam was nearly horizontal and parallel. The beam entered the tunnel near the upper right corner of the entrance (south end) and exited near the lower left of the exit (north end). The beam intersected the ground behind the tunnel at about 1170-m range. Table 1 lists the various aerosols released in the sABT during the tests. Table 2 contains a description of the biological simulants and the agents they are intended to represent.

The APS data presented in this paper are from just one APS located at a range of 1011 m from the lidar. All APS units were located on the floor of the tunnel and draw air in at a rate of 1 liter/min. The aerosol particle count data, in particles per liter (PPL), are integrated only from 1 to 10 \( \mu m \), inclusive, and the mean level of background counts (determined just before and after the release) have been subtracted to obtain the concentration data presented.

Figure 6 shows the raw aerosol backscatter signal from one laser pulse during the release of a simulant in the tunnel. The backscatter signals exhibit sharp rise times at the leading edge of the aerosol-filled section of the tunnel and longer fall times at the exit of the tunnel. The stronger, parallel channel exhibits slower response on both leading and trailing edges than the weaker, perpendicular channel. This illustrates the limited slew rate of the AD829 postamplifier. For example, small-amplitude signals have faster rise and fall times than large-amplitude signals. The data also indicate that the backscatter intensity is stronger at the north end of the tunnel. Figure 7 shows backscatter intensity and depolarization ratio as a function of range through the sABT, calculated from the parallel and perpendicular backscatter signals shown in Fig. 6.

As pointed out in Sec. 2.2, a ND filter wheel was used in the lidar receiver to prevent signals from exceeding the maximum limit of the digitizer quantization and to reduce the risk of damaging the photodetectors from hard target reflections. Because of the short distance between the tunnel and the lidar, and the resulting large strength of the backscatter intensity signals, an ND filter was used at all times during the sABT trials. The setting was manually adjusted several times during the experiment and chosen by the lidar operator based on inspection of signal levels in real time. We assert that changing the amount of attenuation in the receiver by the ND filter should have no effect on the depolarization ratio, because the attenuation takes place prior to the polarization beamsplitter cube and the ND filters should be polarization-independent.

Because the depolarization-ratio measurements are not absolute, we can only compare them with local values for relative changes. Local can be defined as close in time (within a few minutes) or range (within a few kilometers).
We expect that different types of aerosol particles in the tunnel will result in different depolarization ratios relative to that of the ambient natural background. The mean and standard deviation of the depolarization ratio from a region in front of and inside the tunnel are listed as the last two columns in Table 1, respectively, and these data are also plotted in Fig. 8. These values were computed by replaying the lidar data and subjectively selecting time periods when the backscatter intensity in the sample region appeared to be elevated above the background and not changing over time. A 36-m segment that was close to the center of the sample region was chosen. Only periods when the ND filter setting was constant were selected. Aerosol releases typically lasted about 5 min, and from these periods intervals of approximately 2 to 4 min in duration were selected. Therefore, a period of 1 min would result in 7200 samples. Data points that had maximized the digitizer scale were not included.

All 16 trials were conducted during the night of June 9–10, 2005. Operations were conducted at night for the benefit of other lidar systems under test, which are sensitive to visible light. The trials took place during a 5-h period, and nine types of aerosols were under test. Some trials released the same aerosol type, but at different dissemination rates, in order to achieve a significantly different concentration in the tunnel. During the 5-h period, the background aerosol depolarization ratio ranged from 0.24 to 0.18. This trend is shown by the slowly varying height of the background bars in Fig. 8. Of the nine types of aerosols tested, only two, white-pine pollen (WPP) and Bacillus subtilis var. niger (BG), exhibited a depolarization ratio

### Table 1
Trials from the sABT on June 10, 2005. Date and times in UTC. Values superscripted 1 indicate background collected with ND=2.0 just prior to the release in front of the tunnel. WPP is white-pine pollen.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Material</th>
<th>Begin release</th>
<th>End release</th>
<th>ND filter</th>
<th>Max. conc.</th>
<th>Background depol. ratio</th>
<th>Release depol. ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Diesel</td>
<td>4:21</td>
<td>4:26</td>
<td>2.5</td>
<td>NA</td>
<td>0.2436±0.00348(^1)</td>
<td>0.0467±0.00013</td>
</tr>
<tr>
<td>2</td>
<td>OV</td>
<td>4:37</td>
<td>4:42</td>
<td>2.5</td>
<td>25,000</td>
<td>0.2344±0.00333(^1)</td>
<td>0.1994±0.00079</td>
</tr>
<tr>
<td>3</td>
<td>BG</td>
<td>4:54</td>
<td>4:59</td>
<td>2</td>
<td>5,500</td>
<td>0.2160±0.00189</td>
<td>0.2295±0.00089</td>
</tr>
<tr>
<td>4</td>
<td>BG</td>
<td>5:08</td>
<td>5:13</td>
<td>2</td>
<td>4,600</td>
<td>0.2315±0.00329</td>
<td>0.2382±0.00135</td>
</tr>
<tr>
<td>5</td>
<td>BG</td>
<td>5:24</td>
<td>5:29</td>
<td>2</td>
<td>8,750</td>
<td>0.2335±0.00362</td>
<td>0.2470±0.00165</td>
</tr>
<tr>
<td>6</td>
<td>BA</td>
<td>5:38</td>
<td>5:43</td>
<td>2</td>
<td>24,000</td>
<td>0.2300±0.00529</td>
<td>0.1380±0.00033</td>
</tr>
<tr>
<td>7</td>
<td>EH</td>
<td>5:54</td>
<td>5:59</td>
<td>2</td>
<td>10,500</td>
<td>0.2271±0.00261</td>
<td>0.0490±0.00009</td>
</tr>
<tr>
<td>8</td>
<td>Kaolin</td>
<td>7:12</td>
<td>7:17</td>
<td>2</td>
<td>7,500</td>
<td>0.2198±0.00213</td>
<td>0.1620±0.00112</td>
</tr>
<tr>
<td>9</td>
<td>Kaolin</td>
<td>7:27</td>
<td>7:30</td>
<td>1.5</td>
<td>11,000</td>
<td>0.2108±0.00207</td>
<td>0.1585±0.00085</td>
</tr>
<tr>
<td>10</td>
<td>MS2</td>
<td>7:44</td>
<td>7:49</td>
<td>1.5</td>
<td>1,400</td>
<td>0.1939±0.00164</td>
<td>0.0710±0.00027</td>
</tr>
<tr>
<td>11</td>
<td>MS2</td>
<td>7:56</td>
<td>8:01</td>
<td>1.5</td>
<td>9,000</td>
<td>0.1861±0.00126</td>
<td>0.0735±0.00079</td>
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<tr>
<td>12</td>
<td>WPP</td>
<td>8:16</td>
<td>8:21</td>
<td>1.5</td>
<td>5,500</td>
<td>0.1990±0.00173</td>
<td>0.2269±0.00045</td>
</tr>
<tr>
<td>13</td>
<td>YP</td>
<td>8:31</td>
<td>8:36</td>
<td>1.5</td>
<td>2,600</td>
<td>0.1833±0.00162</td>
<td>0.0420±0.00009</td>
</tr>
<tr>
<td>14</td>
<td>YP</td>
<td>8:46</td>
<td>8:51</td>
<td>1.5</td>
<td>19,000</td>
<td>0.1837±0.00190</td>
<td>0.0296±0.00003</td>
</tr>
<tr>
<td>15</td>
<td>Kaolin</td>
<td>9:05</td>
<td>9:10</td>
<td>1.5</td>
<td>100,000</td>
<td>0.2016±0.00238</td>
<td>0.1179±0.00015</td>
</tr>
<tr>
<td>16</td>
<td>EH</td>
<td>9:19</td>
<td>9:24</td>
<td>2.0</td>
<td>800</td>
<td>0.2055±0.00265</td>
<td>0.0466±0.00007</td>
</tr>
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### Table 2
Descriptions of the biological simulants and their abbreviations.

<table>
<thead>
<tr>
<th>Description</th>
<th>Representing</th>
</tr>
</thead>
<tbody>
<tr>
<td>OV</td>
<td>Ovalbumin</td>
</tr>
<tr>
<td>BG</td>
<td>Bacillus subtilis var. niger</td>
</tr>
<tr>
<td>BA</td>
<td>Gamma-killed vaccine strain</td>
</tr>
<tr>
<td>EH</td>
<td>Erwinia herbicola</td>
</tr>
<tr>
<td>MS2</td>
<td>Male-specific bacteriophage type 2</td>
</tr>
<tr>
<td>YP</td>
<td>Gamma-killed vaccine strain KIM of Yersinia pestis</td>
</tr>
</tbody>
</table>
larger than the background depolarization ratio. All other aerosol types exhibited significantly lower depolarization ratios than the background values at that time. The lowest average depolarization ratio was 0.03, and it resulted from a gamma-killed vaccine strain of *Yersinia pestis* (YP). Two other types of aerosols had similarly very low (<0.05) depolarizing ratios: diesel exhaust and *Erwinia herbicola* (EH). We note that YP and EH are termed "wet" simulants by test coordinators. This is consistent with our low depolarization-ratio measurements, which would indicate that they are composed of spherical particles, i.e., droplets. Furthermore, we note that the microphysical characteristics of diesel engine exhaust vary according to the efficiency of the combustion process.

Although the depolarization-ratio measurements shown here are relative, it is reasonable to expect that they will fall within a similar range to those of other polarization lidar measurements. Lee et al. document similar tests of a 523-nm-wavelength photon-counting-receiver lidar at Dugway in April and May of 2006. They report background atmospheric depolarization ratios that vary from slightly more than 0 up to 20% on two dates. All of the data collected at Dugway with the REAL system in the configuration described here indicate background depolarization ratios between 20% and 40%. This difference could be attributed to differences in the background aerosol composition or microphysical characteristics. However, given the remote and arid location of Dugway and the similar weather conditions under which tests are usually conducted, it is more likely that the difference was caused by the way the transmit beam was projected into the beam-steering unit (BSU).

Operation of REAL at the sABT also allowed us to explore the dependence of backscatter intensity and depolarization ratio on simulant concentration as measured by the APS. For brevity, we present just two examples here. The two trials that these figures result from were of the lowest concentration that could be achieved in the sABT with the available aerosol disseminators. Figure 9 shows the REAL backscatter intensity versus concentration of YP as measured by the APS. Unlike the values presented in Table 1 and plotted in Fig. 8, the lidar data points plotted in Fig. 9 were not averaged over time, but only over range. The APS reported concentration once per 10 s. Therefore, we plotted backscatter intensity resulting from every laser pulse at 10 Hz, while the APS concentrations were updated only at 10-s intervals. This is the reason for the clusters of data points in horizontal lines. Also, it is apparent that the lidar...
detects aerosol in the tunnel before the APS—this is evidenced as the cluster of points between 28 and 32 dB and very near 0 PPL concentration. Despite the scatter of data points, a trend is apparent. The relationship has an approximate slope of 2500 PPL per 7 dB. These data were collected with an ND filter setting of 1.5. It is clear from the distribution of the points that concentrations as low as a few hundred PPL of this simulant can be detected at a range of about 1 km under very clear conditions. We note that if the ND filter had been removed, or set to zero, the backscatter signal available to the photodetector would have been more than 30 times greater.

Figure 10 shows the lidar depolarization ratio versus concentration as measured by the APS. These data points were obtained in the same fashion as those shown in Fig. 9, but for a different trial (EH in this case). From this distribution of points, two very different states are obvious. First, a cluster of data points ranging from approximately ±150 PPL and from 0.0 to 0.4 depolarization ratio characterizes the background. The average background during the test had a depolarization ratio of 0.20. These points were collected before the APS and lidar detected the plume. Once the simulant arrives in the sample volume, the APS rises above its noise floor of 150 PPL, the presence of aerosols is also detected by the lidar, and the depolarization ratio suddenly collapses to an average value of 0.047—about the same as reported in Table 1. The plot shows that the depolarization ratio remains approximately constant as the concentration varies. This result (in comparison with a plausible result in which the depolarization ratio had a trend with increasing concentration) indicates that the simulant signal is very dominant over the background signal. This is an encouraging result for the challenging application of plume boundary delineation. Though the backscatter intensity through a plume is likely to change because of varying concentration, the depolarization ratio is not. This characteristic may be useful for algorithms designed to identify and track plumes in surveillance applications.

### 3.2 Scanning and Open-Air Releases

Following the experiments at the sABT, the REAL was moved to a location at Dugway Proving Ground where it could observe open-air releases of simulants at varying distances and multiple simulants simultaneously. Again, for brevity, we present only two cases here. No ND filter was used.

Figure 11 shows total backscatter intensity (left) and depolarization ratio (right) from a single plan position indicator (PPI) scan through two aerosol plumes at 0.6-deg elevation angle. The plume between 2- and 3-km range is white smoke from a point release, and the plume at 1.5-km range is road dust from a moving vehicle. In this case, the white smoke had a lower depolarization while the road dust had a higher depolarization than the background. This result is consistent with the fact that white smoke is composed of spherical oil droplets while road dust is composed of dry, crystalline particles.

Figure 12 shows a single PPI scan through two aerosol plumes at 0.6-deg elevation angle. The plume that emerges near 1 km range is from a point release of MS2 and the plume near 2 km is from an aerial release of BG. The BG resulted in a higher depolarization and the MS2 a lower depolarization than the background. This result is also consistent with the fact that for this case, the BG was released in a dry form (nonspherical particles) while the MS2 was disseminated in a wet form (spherical particles).

Obtaining absolute depolarization with a lidar using a BSU takes special precautions. Reflection by the scanning mirrors has the effect of rotating the polarization vector of the outgoing laser pulse. On propagation back to the receiver, the polarization vector is counterrotated by the same amount. However, if the aerosols have a preferred orientation, the absolute measured depolarization will be erroneous. In addition, mirrors often have different reflection coefficients (i.e., $r_p \neq r_s$) and impart a phase shift (i.e., $\delta_p \neq \delta_s$) between the reflected components, both of which cause errors when scanning. The phase shift transforms linear polarization to elliptical, which is not restored to linear by backpropagation. As is shown in the appendix (Sec. 5), these angle-dependent errors are minimized when scanning at 0-deg elevation with an elevation-over-azimuth scanning BSU. The mirrors in this type of BSU are always oriented 45 deg to the beam’s angle of incidence. In this geometry, the errors imparted by the azimuth mirror are effectively canceled by the elevation mirror. In the results presented here, protective gold coatings were used on the BSU mirrors. These metallic coatings have a differential phase shift ($\Delta\phi = \phi_s - \phi_p$) of 8 deg each and a differential reflectivity ($\Delta r = r_s - r_p$) of 1.3%. All of the results for this study were obtained with the BSU in a near-horizontal scanning mode to minimize angle-dependent errors. However, the optical path used to direct the beam into the BSU still introduced some polarization ellipticity into the final transmitted beam. Exactly how much is unknown. An improved optical layout and coatings are required in order to make absolute depolarization measurements, which are a topic of ongoing work.

### 4 Conclusion

Relative backscatter polarization sensitivity was added to the Raman-shifted Eye-safe Aerosol Lidar (REAL). This
was accomplished by improving the linear polarization purity of the transmitter and separating the backscatter signal into parallel and perpendicular polarization channels. The ratio of these signals, the linear depolarization ratio, is an indicator of aerosol particle sphericity. Results from deployment of the system at Dugway Proving Ground indicate good depolarization sensitivity to several kilometers range and in the form of relative depolarization-ratio.

The plume between 2- and 3-km range is white smoke from a point release, and the plume at 1.5-km range is road dust. In this case, the white smoke had a lower depolarization while the road dust had a higher depolarization than the background aerosol (∼11% lower and ∼8% higher, respectively.)

The plume that begins near 1-km range is from a point release of male-specific bacteriophage type 2 (MS2, a bacteriophage representative of viral agents), and the plume near 2 km is from an aerial release of BG. The BG resulted in a higher depolarization and the MS2 a lower depolarization than the background aerosol.
changes caused by varying types of biological aerosol simulators and other particulate matter. Depolarization-ratio departures from the background are consistent with our limited understanding of the phase (wet or dry, droplets or crystals) of the various materials. Furthermore, since the depolarization-ratio signature of all the plumes departed from the background by measurable amounts, we expect this technique would be useful in urban environments to delineate potentially hazardous plumes from the background. Detection and tracking of plumes in the urban environment is significantly more challenging because of the large number of aerosol sources and the rarity of the ideal weather conditions chosen for testing at Dugway. We hope to test this hypothesis by field deployment of the system in an urban area.

Sources of error in the depolarization-ratio measurements are known to be the result of polarization-sensitive coatings in the present beam-steering unit, secondary mirror of the telescope, and transmit beam delivery mirrors. In the future, we intend to recoat these optics to have matched reflectivity and zero phase shift in an effort to move towards measuring absolute depolarization ratios.

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Appendix

In a formalism similar to that of Bissonnette et al., the transfer matrix for an electric field reflected off a mirror can be expressed as

\[
M(\theta_u, \theta_v) = \begin{bmatrix}
  C_1 \sin \theta_e \cos \theta_u + C_3 \cos \theta_e \sin \theta_u & C_1 \sin \theta_e \sin \theta_u - C_3 \cos \theta_e \cos \theta_u \\
  -C_2 \sin \theta_v \sin \theta_u + C_3 \cos \theta_v \cos \theta_u & C_2 \sin \theta_v \cos \theta_u + C_3 \cos \theta_v \sin \theta_u
\end{bmatrix},
\]

(1)

where \( \theta_u \) and \( \theta_v \) are the transmitted azimuthal and elevation angles, respectively, and \( C_1 = r_p^2 \exp(2i\phi_p) \), \( C_2 = r_r^2 \exp(2i\phi_r) \), and \( C_3 = r_f^2 \exp[i(\phi_f + \phi_f)] \). In the case of horizontal scanning (\( \theta_u = 0 \)), Eq. (2) simplifies to

\[
M(\theta_v) = \begin{bmatrix}
  C_3 \sin \theta_u & -C_3 \cos \theta_u \\
  C_3 \cos \theta_u & C_3 \sin \theta_u
\end{bmatrix}.
\]

(3)

Under this condition, an equivalent amplitude change and phase shift, \( r_p r_f \exp[i(\phi_p + \phi_f)] \), is applied to both the x and y fields at any azimuthal angle. Therefore, a linearly polarized field incident on the BSU mirror pair remains linearly polarized after reflection at all azimuthal angles.

References


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