Test and Evaluation of Lidar Standoff Biological Sensors

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A high priority for the U.S. military is to develop the ability to provide early warning of a remote biological warfare agent attack so that protective measures can be taken before personnel are subjected to infectious or lethal doses of the aerosol cloud. One way to achieve this goal is to use lidar sensors that can detect the presence of an aerosol cloud at ranges out to 10 km and discriminate whether the cloud is biological or nonbiological at ranges out to 3 to 4 km. This article describes the testing of aerosol lidar sensors, including procedures for evaluating sensitivity and cloud detection, and a new method of calibration using a standoff ambient breeze tunnel. Preliminary results from the tunnel show a significant improvement in calibration accuracy over the traditional method of using open-air disseminations. APL is developing an end-to-end lidar model to extend the tunnel sensitivity measurements, at 1 km, to longer ranges.

BACKGROUND

The principles of operation for lidar (light detection and ranging) are similar to those for radar: a light pulse is transmitted and its return signal is range gated. The wavelength of the laser is chosen to be compatible with the aerosol particle sizes of interest. Here, we are interested in particles with diameters in the 1- to 10-μm range, which are readily transported by the wind over relatively long distances (kilometers) and easily inhaled. (Larger particles quickly fall to the ground, and smaller particles are not trapped by the respiratory system.) At wavelengths in the infrared (IR) range of 1000–1500 nm, depending on the size, availability, and cost of the laser, the backscattered light from aerosol particles in the 1- to 10-μm range can be detected without difficulty. In contrast, a 10-GHz radar has a wavelength of 3 cm or orders of magnitude longer than the 1- to 10-μm particles, making it an inefficient system for aerosol detection.

If the atmosphere were clear of any aerosol except during a biological warfare agent attack, the problem of detecting the attack would be solved using only the IR lidar. However, IR lidar can also detect naturally occurring pollen, industrial pollution, road dust, diesel exhaust, and burning vegetation, and these sources of interfering aerosols lead to an undesirably high false alarm rate.

Lidar systems currently cannot identify a particular biological warfare agent attack within an aerosol cloud, but they can discriminate between biological and nonbiological aerosols. This capability allows military commanders to take steps to protect soldiers (e.g., having them wear masks) before the biological cloud reaches them. A lidar system's discrimination mechanism relies on transmitting ultraviolet (UV) light and detecting the wavelength-shifted UV fluorescence (UVF) that is produced by all biological material. The fluorescence is a relatively weak light source compared to the elastic backscattered light from aerosol particulates for either the transmitted IR or the UV; hence, the detection performance of the UVF is significantly lower, for a given laser power, than the backscatter detection performance.

To measure detection performance, a discrimination algorithm originally developed by the Massachusetts Institute of Technology Lincoln Laboratory[1] is used. The algorithm is based on a scatter plot of the ratio of the fluorescence signal to the UV backscatter signal for biosimulants (*Bacillus globigii*, an anthrax simulant; *Erwinia herbicola*, a vegetative bacteria simulant; and male-specific coliphage type 2, an infectious viral simulant) and interferents such as road dust, diesel exhaust, burning vegetation, and smoke. A threshold is adjusted so that the simulants result in ratios above the threshold, and interferents result in ratios below the threshold. Other discrimination algorithms that are based on the spectrally resolved fluorescence signature of simulants and interferents (rather than the broadband fluorescence signal) are currently under investigation and may result in improved discrimination performance.

Open-air disseminations typically used for calibrating lidar sensors have two major deficiencies. First, the concentration of the aerosol cloud is difficult to measure using a limited number of aerosol particle sizer (APS) sensors because variations in wind direction during the measurement period often cause the cloud to either miss the APS sensors completely or pass over them with varying degrees of concentration. Second, waiting for the winds to return to the desired direction to execute the next release causes considerable delay, greatly adding to the cost of the test. These deficiencies have been somewhat overcome by using the XM-94 lidar, developed by Los Alamos National Laboratory (LANL), as the "referee" sensor. The XM-94 lidar can accommodate significant variations in wind direction and wind speed because it covers a large surveillance area as it scans. However, it was calibrated using APS sensors during open-air releases, and therefore, the accuracy of the measured cloud concentration is reported by LANL to be within a factor of ≈2.

Calibrating another lidar using the XM94 as a referee is relatively straightforward. The two sensors are placed side by side, staring in a direction that is perpendicular to the nominal wind direction. Aerosol releases are generated off-axis from the lidar line of sight and at fixed ranges from the sensors, typically 1, 3, and 5 km. The peak signal, at a given range, from each sensor is determined via data processing. Figure 1 shows an example of crosswind peak signals, at a range of 3 km, from the XM94 and a system under test (SUT). A least-squares fit is performed between the two time series for a region where the signal-to-noise ratio is greater than 10. The

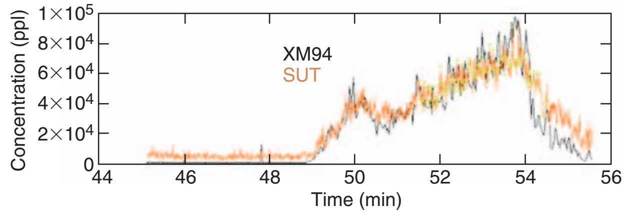

Figure 1. Comparison of maximum signals, after background subtraction, between the XM94 lidar and a system under test (SUT) from a crosswind release at 3 km.

resulting scale factor allows the conversion of the measurement units from the SUT to the desired concentration units of particles per liter (ppl).

System sensitivity is estimated by multiplying the scale factor times a noise level that is four standard deviations above the background noise (combined ambient aerosol "noise" and sensor system noise). The four standard deviation criterion was selected to provide acceptable detection performance with reasonably low false alarms.

To reduce the relatively large errors in quantifying sensitivity and to improve the efficiency of the testing procedure, we are investigating a new approach that potentially provides better control of the target aerosol cloud concentration. This approach uses an open-ended tunnel that maintains an aerosol cloud through some portion of its length. APS sensors are used to monitor cloud concentration over that length. The SUT is positioned about 1 km from the tunnel entrance so that the lidar's beam is through the tunnel.

Battelle Memorial Institute developed the Ambient Breeze Tunnel (ABT) for testing "point" biological sensors. Primarily because of its construction, the tunnel does not have a "see-through" capability; it cannot be used for lidar testing without major modification. Therefore, Battelle designed a second tunnel, the "standoff ABT" (sABT),[2] which is positioned next to the ABT so that the ABT blower, with suitable baffling, can be used to pull air through either tunnel. The blower provides the necessary airflow which, combined with a steady flow from the aerosol disseminator, results in a reasonably constant aerosol cloud concentration within the tunnel. Figures 2 and 3 show the ABT and sABT at Dugway Proving Ground, Utah. Note the "connection" between the two tunnels and the baffle in the ABT required to shunt airflow through the sABT. The sABT is approximately 250 ft (76 m) long.

RESULTS

Preliminary characterization measurements in the sABT were obtained in February 2003 to determine the uniformity of the aerosol cloud concentration within the tunnel. The APS sensors were placed at various locations within the tunnel to measure concentration

Figure 2. Photograph of the Ambient Breeze Tunnel (ABT) and standoff Ambient Breeze Tunnel (sABT) at Dugway Proving Ground.

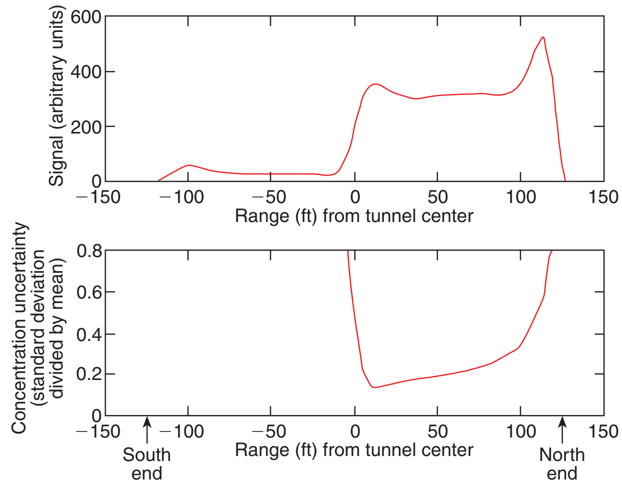

Figure 4. *Bacillus globigii* cloud (top) mean concentration and (bottom) concentration variability within the sABT measured by the Dugway West Desert Test Center lidar positioned 1 km from the tunnel. The dissemination starts just beyond 110 ft (33.5 m) north of the tunnel center. Less than 10% change in concentration is seen between 30 and 90 ft (9 and 27 m, respectively). Note the increase in concentration prior to leaving the tunnel at its center.

gradients along axis, across axis, and vertically. Simultaneous APS and lidar measurements of the cloud concentration were taken in April and May 2003, with the lidar positioned approximately 1 km from the tunnel. Preliminary results (Fig. 4) from the Dugway West Desert Test Center's lidar (wavelength = 1064 nm, range resolution = 1.5 m) show that a relatively uniform cloud concentration can be maintained in the tunnel from 25 to 90 ft, north of the tunnel's center, with variability ranging between 15 and 30%. The mean concentration in Fig. 4 (top) was obtained over a 10-min averaging period, representing a potential order of magnitude improvement in the accuracy of determining sensitivity over open-air releases.

One lesson learned from the February testing was that the sABT was susceptible to damage during periods of high winds. The open tunnel acted as a fluttering wind sock that ripped under sustained high winds. End covers were manufactured to prevent this from reoccurring. Zippered window flaps, approximately 2 × 2 m, were added to the end covers to allow continuation of lidar testing during moderate to moderately high wind conditions.

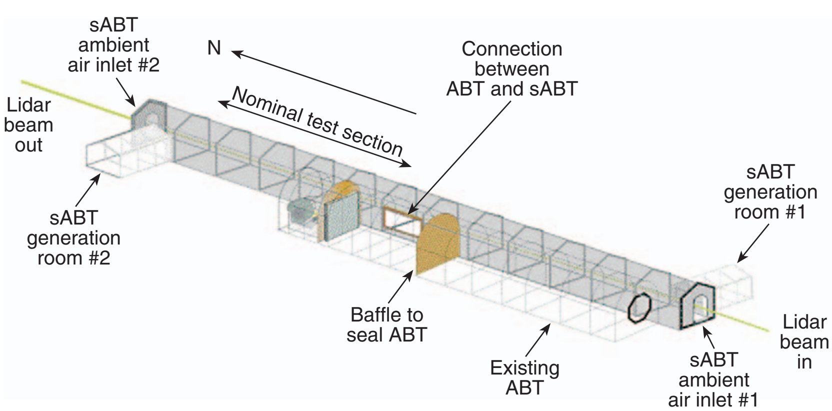

Figure 3. Schematic of the ABT and sABT.

DISCUSSION

The processing required to quantify the sensitivity of the tunnel measurements is shown in Fig. 5. The scale factor to convert the lidar measurement units to concentration units of particles per liter is determined from the APS aerosol concentration measurement in the tunnel with the corresponding range-resolved lidar aerosol signal that is closest to the APS. The aerosol signal is the total lidar return signal, which consists of the ambient atmospheric signal plus the aerosol signal from the tunnel dispersion minus the mean ambient signal. An estimate of sensor sensitivity is obtained by multiplying the standard deviation of the ambient background noise by 4 and then applying the scale factor to convert the sensitivity to units of particles per liter. The factor of 4 was chosen to provide a probability of detection of 0.9 assuming Gaussian statistics for the background noise.

For sensitivity measurements, the lidar system is constrained to operate in a "stare" mode in which the azimuth angle is fixed. During normal surveillance operations, however, the system is continuously scanning the horizon for possible biological aerosol clouds. The process involves detecting the presence of a cloud from a single scan and then, if a cloud is detected, deciding where to point the lidar to "co-add" on the cloud. The co-add operation is required to collect and integrate sufficient UVF data for a detection. This low-level signal typically

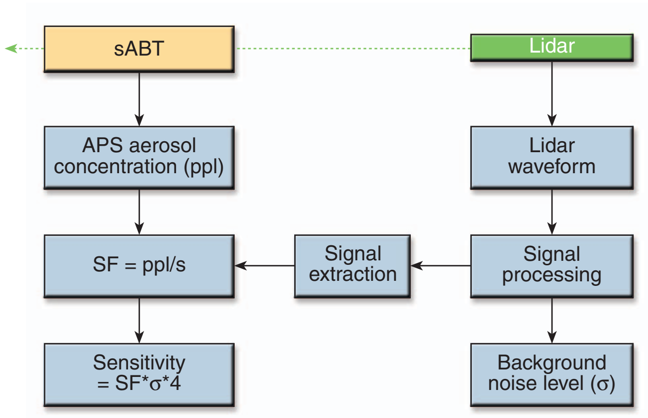

Figure 5. Sensitivity processing diagram for sABT and lidar measurements (APS = aerosol particle sizer, ppl = particles per liter, SF = scale factor).

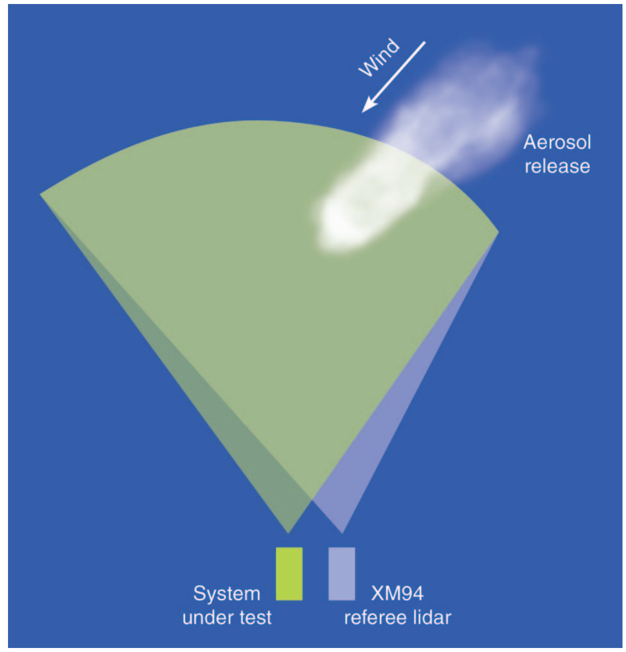

Figure 6. Concept for downwind releases.

requires 10 s of stare time. If a UVF detection is made, sensor processing must continue in order to determine whether a biological discrimination can be ascertained from the data.

The lidar sensor operational evaluation consists of quantifying the following from downwind simulant, interferent, and combined simulant/interferent releases:

- Probability of discrimination
- Range at which the discrimination is first made
- Early warning time (time it takes the detectable cloud to reach the lidar based on discrimination range and wind speed)
- Number of false discriminations made during testing
- Observed reliability of the sensor during testing

The concept for the downwind release test setup is shown in Fig. 6. For each release, the XM94 lidar is used as a referee sensor to confirm the detection and discrimination obtained by the SUT. If the SUT does not detect the target cloud, the referee lidar is used to check that the cloud is in the field of view of the SUT and that the cloud concentration is above the sensitivity level of the SUT. If these conditions are met, the release is scored as a missed detection. Similarly, if the SUT makes a biological discrimination, the range and azimuth of the corresponding cloud detection are checked against the point at which the referee sensor has located the cloud. If there is agreement, the discrimination is scored as correct; if there is disagreement, the discrimination is scored as a false alarm.

APL is developing an end-to-end lidar model[3] as a tool to predict sensor performance and to provide insight into whether a design parameter or a model parameter needs better quantification when measured and predicted performance differ significantly. The concept for the model this shown in Fig. 7.

The end-to-end model has four major components: lidar design parameters, biological aerosol parameters, ambient irradiance from the Moon or urban backlighting, and atmospheric visibility. For a biological cloud concentration and a specified lidar design, the model predicts the signal-to-noise ratio as a function of range and visibility. The end-to-end model has been checked against lidar models developed by two independent outside vendors, and good agreement (within a factor of 2) has been achieved in these comparisons, with differences attributable to the small details in the way certain design parameters are formulated by different modelers.

The end-to-end model serves three functions: (1) to verify performance claims from vendors with new designs, (2) to identify faulty lidar design parameters when measured performance falls short of predicted performance, and (3) to provide programmatic guidance to focus additional work on those parameters that are not well quantified. An example is the backscatter coefficient and fluorescence cross section for *Bacillus globigii* at a 355-nm excitation wavelength for which the few experimental results that have been published vary by an order of magnitude. Validation of the model against data is an ongoing process that is awaiting additional high-quality field test data. As confidence in the model increases through the validation process, sensitivity predictions will become more reliable, thereby reducing the time and cost of sensitivity testing.

CONCLUSION

The sABT is a very useful facility for calibrating aerosol lidar sensors, significantly reducing the calibration errors by an order of magnitude over calibrations obtained from open-air releases and greatly

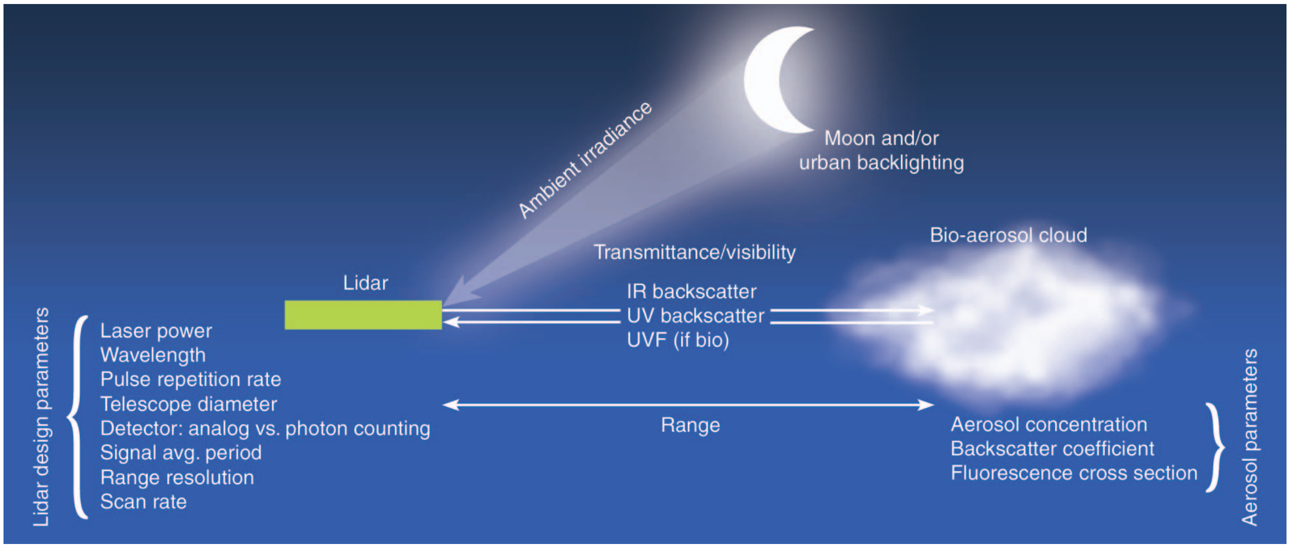

Figure 7. The end-to-end lidar model. For a biological cloud concentration and a specified lidar design, the model predicts the signal-to-noise ratio as a function of range and visibility.

improving the testing efficiency. Future validation of the lidar model will allow an accurate prediction of the lidar's sensitivity, evaluated from the tunnel measurements at 1 km, to other range and visibility conditions.

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