Optimization of obscurant penetration with next generation LiDAR technology

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ABSTRACT
Neptec Technologies’ next generation OPAL 3D LiDAR uses multi-detection technology for penetrating obscurants to detect objects. This multi-returns LiDAR system can receive up to 7 returns from one single laser pulse. Based on a Risley prism scanning mechanism, the OPAL Performance Series (Third Generation), employs independent motor control to spin both prisms and generate optimized scan patterns with customized fields-of-view from 30° to 120°. The OPAL-P500 was recently evaluated to detect specific objects of various reflective indices within a controlled obscurant chamber capable of generating a number of aerosol obscurants. Obscurants used in this investigation include: Arizona road dust and water fog. The obscurant cloud optical densities were monitored using a transmissometer. A series of six mesh screens were placed in the chamber, with solid targets at the far end of the chamber and with no obscurants present in the air. In this test scenario, the number of return pulses and their relative strengths were validated from a single laser pulse/shot. These meshes were placed at various distances from each other to characterize the detection probabilities in clear conditions. Alternatively the meshes were removed and the solid targets remained at the back of the chamber to validate the OPAL-P500 target detection performance in obscurants of varying densities. The data from a number of testing scenarios will be presented to observe and analyze the effects of obscurants and target reflectivity using the OPAL-P500’s multi-returns LiDAR technology.

Keywords: LiDAR, Obscurants, Controlled Conditions, Optical Depth, Extinction Coefficient

1. INTRODUCTION
LiDAR sensors have proven their usefulness in providing high spatial resolution 3D information in the environment they operate in. In addition, recent years have seen several advances in LiDAR hardware technologies contributing to the reduction of typical LiDAR SWaP (Size, Weight and Power) as well as its affordability. As a result, LiDAR sensing is becoming ubiquitous in a large number of applications, including guidance and navigation, surveying, surveillance, and security. Of particular interest is the use of 3D LiDAR for either autonomous transportation or user-controlled platforms where situational awareness necessitates high spatial resolution. Examples include the use of 3D LiDAR to assist in autonomous car navigation and for pilot-assist applications when flying helicopters in poor visibility¹²,³⁴.

The main natural manifestations of poor visibility are attributable to rain, fog, snow, dust, and smoke. The ability of a LiDAR sensor to penetrate such obscurants will depend upon a number of factors, including the emitted pulse peak power and the LiDAR’s detector sensitivity. Various estimates of range penetration in obscurant conditions in relation to obscurant type and density have been reported for the previous generation of OPAL LiDAR⁵,⁶,⁷. The current OPAL Performance Series LiDAR has the ability to detect up to seven returns from multiple targets illuminated by the same laser pulse. One objective of this research was to test the multi-return capability by using a number of mesh screens positioned at regular intervals. This measurement approach was also used to estimate the spatial resolution limit of the LiDAR. The tests were done in a controlled aerosol chamber at Defence Research and Development Canada (DRDC) in Valcartier, Quebec, Canada.

A secondary objective was to quantify the penetration of obscurants of the OPAL-P500 LiDAR. Tests were done using water fog and Arizona Road Dust (ARD) obscurants. The material, methods and main results are presented in the subsequent sections.
2. MATERIAL & METHOD

2.1 LiDAR sensor high-level architecture

Neptec Technologies’ third generation OPAL Performance Series 3D LiDAR, OPAL-P500 and OPAL-P1000, operate at a wavelength of 1550nm and uses a single-mode pulsed fiber laser. The scanning mechanism is based on the Risley prism pair principle in which each prism is rotated under independent motor control to generate unique, non-overlapping scan patterns. The patterns are distributed in a conical FOV with a higher data density towards the center of the FOV. The maximum data acquisition speed is achieved at a Pulse Repetition Frequency (PRF) of 300kHz and the laser average power is at 300mW. The range measurements are performed using the Time-Of-Flight (TOF) methodology. Additional information on the OPAL 3D LiDAR architecture may be found in [8] and [9]. The OPAL-P500 unit also features the capability to acquire up to seven returns (or reflections) per emitted laser pulse; this is especially useful to penetrate through vegetation or through other porous material to acquire returns on objects that are behind such hindrances. High-resolution mapping of forested areas from an aerial platform is an example of the use of multi-returns capability where the tree tops are detected as well as the branches and the ground level below. The multi-return functionality is used for this study to validate the feature experimentally and to measure the spatial resolution.

Figure 2-1. Picture of the OPAL-P500 installed on a tripod.

2.2 Controlled aerosol chamber & related equipment

The controlled aerosol chamber is shown in Figure 2-2 (a). It is a 24.4m long structure with matte black painted in the interior walls to minimize reflections. Both ends of the chamber are sealed with fast opening roller type garage doors, allowing the chamber to be filled with a specific amount of obscurant. Fans on both sides of the chamber close to the floor are used to evenly distribute the obscurants inside the chamber. When a desired obscurant density is reached, the doors are remotely opened and the LiDAR starts scanning the targets arranged inside the chamber. Figure 2-2 (b) shows the chamber with water fog.

The aerosols used for this study include water fog, and Arizona Road Dust (ARD). The water fog is generated using BEX Spray Nozzles PV36 producing water droplets in the range of 10µm to 20µm in diameter. The ARD is generated with a Venturi-type nozzle spraying PTI ISO 12103-1 dust particles in the range of 1µm to 11µm in diameter.

Independent transmissometers measure the transmission of light through the dust cloud at wavelengths of 532nm, 1064nm, and 1560nm. The transmission measurements as well as the LiDAR data are both time-stamped and can then be correlated in the course of the tests.
2.3 Multi-returns targets

The validation of multi-returns capability as well as spatial resolution was accomplished using mesh screens spaced at regular intervals. A total of six screens were placed in the chamber. Figure 2-3 (a) and (b) show the screens arrangement. The first screen is at a fixed position from the entrance door of the chamber; tests were performed with separation distances between the screens of 1m, 2m, and 4m. A target placed at the back of the chamber, beyond the set of screens, can also be seen in the right picture. The target is a plywood board with a matte white painted section with a 75% reflectivity and a matte black painted section with a 5% reflectivity.

2.4 Multi-returns data acquisition method

Figure 2-4 shows the relative positioning of the screens, target, and LiDAR in the aerosol chamber. For these tests, the emitted laser beam is held stationary through software control and is pointed at the target at the back of the chamber; it has to propagate through each mesh screen to reach the target. Each screen has a light transmission of about 80%. The laser’s pulse repetition rate is set at 25kHz and the waveform return for each laser pulse is digitized at a 2.5GHz sampling frequency. The sampling interval corresponds to a range resolution of 0.06m. Each waveform is limited to 1024 samples and several waveforms are acquired for each test.
3. MULTI-RETURNS & SPATIAL RESOLUTION RESULTS

3.1 Waveforms measurements

During the tests, the laser was pulsed at 25kHz with a pulse peak power of 3.0kW. For each laser pulse, the return waveform is digitized and saved for analysis. The LiDAR is positioned at about 53m from the target and at 30.7m from the first mesh in the chamber. A picture of the target is shown in Figure 3-1 (d). The multi-returns tests were performed in clear conditions.

Figure 3-1 (a), (b), and (c) show the results obtained for mesh separations of 1, 2, and 4 meters, respectively. Each graph represents the average return intensity signal using 660 individual waveforms. The first observation is that in most cases there is a measurable return intensity at the expected positions of each mesh screen. Pulse returns can be seen for all the meshes and also for the target with 2m and 4m separation intervals. In the case of the 1m separation interval, the last mesh screen is not detected and the return intensity from the target is very low. It can also be observed that the intensity of the returns of the last mesh screen and the target are stronger as the mesh screens separation increases.

It can be observed from the graphs in Figure 3-1 that there is a dependence of the return intensity on the separation distance between mesh screens. One possible reason may have to do with the beam size. The beam has a waist size of ~3.2mm and a full divergence angle of 0.85mrad. When the mesh screens are separated by a small distance, such as a 1 meter separation, the beam area will be smaller when going through the 1 meter spaced meshes than it would be when passing through mesh screens spaced further apart. A smaller beam size will proportionately have a larger portion of its area being blocked by the mesh strands and therefore a lower transmission through the mesh. This effect remains to be tested experimentally.

3.2 Spatial resolution limit

A second main observation related to the measured waveforms is that each mesh screen is very well resolved without any ambiguity. The theoretical spatial resolution of two objects located in a single beam is given by equation (1) below, where τ is the pulse width, c is the speed of light, and ΔR is the spatial resolution[^10].

\[ \Delta R = \frac{\tau c}{2} \]

The OPAL-P500 uses a pulse width of 4ns and using equation (1), the range resolution of two objects contained in the same beam is 0.6m. Figure 3-2 (a) and (b) show LiDAR scan data obtained during a full scan of the screens in the chamber using a PRF of 25kHz; the colour code for the data points uses red to green to represent lower to higher pulse return intensities. In image (a), the mesh screens separated by 0.5m are not differentiated whereas in image (b) they are separated by 1m and are well differentiated. As can be seen, it is not possible to differentiate the screens separated by 0.5m whereas it is possible to distinctly identify all the six screens separated by 1.0 meter. The experiment confirms the expected resolution limit of 0.6m.
Figure 3-1. Results obtained from the waveforms measurements. (a) 1m mesh screen separation; (b) 2m mesh screen separation; (c) 4m mesh screen separation; (d) target at the back of the chamber.

Figure 3-2. Full scan of the chamber in clear conditions; (a) mesh screens are separated by 0.5m; (b) mesh screens are separated by 1m.
4. OBSCURANTS PENETRATION

4.1 Detection modes

Detection modes using either the rising edge or falling edge of the target return pulse are illustrated in Figure 4-1 (a). The waveform signal was obtained in fog obscurant conditions; the first wide return signal corresponds to the reflection of the laser pulses incident on the fog cloud whereas the last pulse corresponds to the reflection from the white target. For most of the experiments carried out in the aerosol chamber, the return signal from the target, when detected, was well isolated from the returns caused by aerosols and was always detected as the last pulse. For most of the tests, the use of the rising or falling edges resulted in similar detection performances. Figure 4-1 (b) shows an example where the falling edge detection is especially useful in situations where the ground level needs to be detected under obscurant conditions from an aircraft.

Figure 4-2 shows the arrangement used for the obscurant penetration tests. The OPAL-P500 is positioned at 12.8m from the front door of the aerosol chamber. The target shown previously in Figure 3-1 (d) is positioned at the back of the chamber at a distance of 23.9m from the front door. The chamber has a length of 24.4m and is filled with obscurants with its doors closed. ARD and water fog are used as obscurants. After the chamber is filled with a dense cloud of obscurants, the front door is then opened to let the LiDAR fully scan the interior of the chamber. Both the LiDAR and the transmissometer data are time-stamped for ease of correlation. The transmissometer receiving detectors are positioned next to the white section of the target and measure the transmission across the column of aerosols.

Using this method, the LiDAR return data can be correlated to the actual light transmission value (and therefore optical depth) prevailing at the time of the laser pulse emission. The analysis determines at what point in time the signal from the target becomes clearly detectable. This will in turn determine the minimum transmission value at which the OPAL-P500 is able to detect the target under the conditions of the experiment.

Figure 4-1. (a): Target detection using rising edge versus falling edge. (b) Benefits of falling edge mode in applications such as ground level detection in obscurants.

Figure 4-2. OPAL-P500 LiDAR setup relative to aerosol chamber and target.
4.2 ARD obscurant

Figure 4-3 shows the penetration performances of the LiDAR through ARD obscurants, for the white and black segments of the target when operating at a PRF of 25kHz, and using the rising edge (a) and the falling edge (b). The graphs show the detected target positions versus the transmission value measured by the 1560nm wavelength transmissometer. When the transmission is high enough to allow detection, the target is detected at its correct range of 36.7m from the sensor. The white and black segments of the target have a reflectivity estimated at 75% and 5%, respectively. As would be expected, the detection of the black segment occurs at higher values of transmission because less energy is reflected by the low reflectivity black target. Figure 4-4 shows similar graphs of detection results obtained when operating with a PRF of 100kHz. As shown in the graphs, the detections occur at higher values of transmission because the pulse energy at 100kHz has only 25% of the energy at 25kHz. Results obtained from the rising edge are comparable with the ones obtained with the falling edge; this is expected as most tests fall in the situation described in Figure 4-1 (a), where the return pulse from the target is usually well isolated from the rest.

The image on the right of Figure 4-5 shows the LiDAR data obtained on the white section of the target at a transmission value of 0.026; the data is colour-coded in intensity with blue showing high intensities and red the low intensities. The high-intensity returns on the left of the target correspond to a small retro-reflector target and the one on the right correspond to the transmissometer receiving optics.

Figure 4-3. Target range measurements vs transmission through Arizona Road Dust (ARD) for the black and white targets. (a): with rising edge mode; (b): with falling edge mode. LiDAR data acquisition is done at 25kHz.

Figure 4-4. Target range measurements vs transmission through Arizona Road Dust (ARD) for the black and white targets. (a): with rising edge mode; (b): with falling edge mode. LiDAR data acquisition is done at 100kHz.
A video of the target was acquired during the tests. The image at the center of Figure 4-5 shows an image of the white section of the target obtained at the same transmission value. Although the white portion of the target is clearly detected by the OPAL-P500, it is not visible to the naked eye.

Figure 4-5. White portion of the target in clear conditions (left); LiDAR data obtained at transmission of 0.026 in ARD (right); corresponding picture of the target white area obtained at the same transmission value (center). PRF is at 25kHz.

4.3 Fog obscurant

Figure 4-6 and Figure 4-7 show the results obtained for the penetration of fog at PRFs of 25kHz and 100kHz respectively, and also for the rising and falling edge detection modes. The penetration performances at PRF of 25kHz are similar for the ARD and the fog in the sense that we start to detect the target at similar transmission threshold values. However, the detections at 100kHz are sparser for the fog when compared to the ARD in the same conditions. The reason for this behaviour is not well understood. Each time the aerosol chamber is filled with an obscurant, the distribution will be specific to each test and cannot be exactly reproduced for other tests. Therefore it is possible that the fog cloud distributions were somewhat different at the time the data was collected at a PRF of 100kHz.

The image on the right of Figure 4-6 shows the LiDAR data obtained on the white section of the target at a transmission value of 0.026; the data is colour-coded in intensity with blue showing high intensities and red the low intensities. A video of the target was acquired during the tests. The image at the center of Figure 4-6 shows an image of the white section of the target obtained at the same transmission value.

Figure 4-6. Target range measurements vs transmission through fog for the black and white targets. (a): with rising edge mode; (b): with falling edge mode. LiDAR data acquisition is done at 25kHz.
Figure 4.7. Target range measurements vs transmission through fog for the black and white targets. (a): with rising edge mode; (b): with falling edge mode. LiDAR data acquisition is done at 100kHz.

Figure 4.8. White portion of the target in clear conditions (left); LiDAR data obtained at transmission of 0.026 in fog (right); corresponding picture of the target white area obtained at the same transmission value (center). PRF is 25kHz.

4.4 Obscurant penetration results analysis

The availability of the transmission values at the time of the target detection can be used for further analysis of obscurant penetration capabilities. The transmission values are related to the aerosol extinction coefficient per unit of length through the Beer-Lambert’s law:

\[ T = e^{-\alpha L} \]  \hspace{1cm} (2)

where,

- T: Transmission value
- \( \alpha \): The extinction coefficient (m\(^{-1}\))
- L: Path length of travel through aerosols (m)

Table 4-1 outlines the minimum transmission values at which the OPAL-P500 LiDAR operating at 25kHz PRF started to detect the white and black targets and their equivalent extinction coefficients obtained from equation (2). This is done for the tests using the rising and falling edge detection methods in ARD and fog obscurants. Table 4-2 shows similar results obtained with the OPAL-P500 LiDAR operating at 100kHz PRF. The transmission values are extracted from the graphs shown in Figure 4-3 and Figure 4-4 for the ARD and fog obscurants, respectively. The minimum transmission values correspond to the points in the graphs when the target starts to be detected in a consistent manner; this is indicated by the arrows in the graphs. Outlier detected data points are not used because they may represent an isolated detection due to inhomogeneity of the obscurant’s cloud distribution. The value of L corresponds to the extent of the obscurant cloud in-between the target and the LiDAR; this is shown in Figure 4-2 to be 23.9m.
A self-consistency estimate of the measured extinction coefficients can be done by using the standard LiDAR equation to evaluate the actual thickness of the obscurant cloud. From the standard LiDAR equation we have:

$$P_{min} = P_0 \frac{\Delta \eta G(R) e^{-2 \int_0^L \alpha(r) dr}}{\pi R^2}$$  \hspace{1cm} (3)

where,
- $P_{min}$: The threshold detection power of the LiDAR receiver (W)
- $P_0$: The emitted laser pulse peak power (W)
- $A$: The aperture of the detector ($m^2$)
- $\rho$: The reflectivity of the target
- $\eta$: The optical efficiency of the LiDAR unit
- $G(R)$: The overlap function between the laser beam and the receiver
- $R$: The range between the LiDAR and the target (m)
- $\alpha(r)$: The extinction coefficient ($m^{-1}$)
- $L$: Thickness of the aerosol cloud (m)

By using the known values of the OPAL-P500 parameters and the values of $\alpha$ obtained from (2), equation (3) can be used to solve for the cloud thickness $L$. The predicted value of the obscurant clouds is shown in Table 4-1 and Table 4-2. From Figure 4-2 we would expect to calculate a value of $L$ close to 23.9m. In most cases the calculated values are close to the expected value of 23.9m. The values tend to be slightly higher when calculated using the white target and slightly lower when using the black target. Their estimated reflectivity values are of 75% and 5% respectively. There is however uncertainty as the reflectivity may have changed slightly during the tests due to dust and or water deposits on the target surface. Also there are variations between the tests as each test will produce different cloud dynamics. Other possible causes of uncertainties include the column of obscurants probed by the transmissometer being slightly different from the column traversed by a given laser pulse.

<table>
<thead>
<tr>
<th>Obscurant</th>
<th>Min Tx Rising edge</th>
<th>$\alpha(m^{-1})$ Rising edge</th>
<th>Predicted thickness of obscurants cloud (m)</th>
<th>Min Tx Falling edge</th>
<th>$\alpha(m^{-1})$ Falling edge</th>
<th>Predicted thickness of obscurants cloud (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARD white target</td>
<td>0.028</td>
<td>0.15</td>
<td>25.4</td>
<td>0.026</td>
<td>0.153</td>
<td>25.0</td>
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<tr>
<td>ARD black target</td>
<td>0.082</td>
<td>0.105</td>
<td>23.9</td>
<td>0.085</td>
<td>0.103</td>
<td>24.3</td>
</tr>
<tr>
<td>Fog white target</td>
<td>0.020</td>
<td>0.164</td>
<td>23.6</td>
<td>0.025</td>
<td>0.154</td>
<td>24.9</td>
</tr>
<tr>
<td>Fog black target</td>
<td>0.067</td>
<td>0.113</td>
<td>22.6</td>
<td>0.07</td>
<td>0.111</td>
<td>22.8</td>
</tr>
</tbody>
</table>

Table 4-1. Summary of obscurant penetration results obtained at 25kHz PRF

<table>
<thead>
<tr>
<th>Obscurant</th>
<th>Min Tx Rising edge</th>
<th>$\alpha(m^{-1})$ Rising edge</th>
<th>Predicted thickness of obscurants cloud (m)</th>
<th>Min Tx Falling edge</th>
<th>$\alpha(m^{-1})$ Falling edge</th>
<th>Predicted thickness of obscurants cloud (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARD white target</td>
<td>0.05</td>
<td>0.125</td>
<td>25.1</td>
<td>0.06</td>
<td>0.118</td>
<td>26.3</td>
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<tr>
<td>ARD black target</td>
<td>0.147</td>
<td>0.08</td>
<td>23.0</td>
<td>0.143</td>
<td>0.081</td>
<td>22.8</td>
</tr>
<tr>
<td>Fog white target</td>
<td>0.10</td>
<td>0.096</td>
<td>31.1</td>
<td>0.05</td>
<td>0.125</td>
<td>25.1</td>
</tr>
<tr>
<td>Fog black target</td>
<td>0.15</td>
<td>0.079</td>
<td>23.2</td>
<td>0.106</td>
<td>0.094</td>
<td>20.4</td>
</tr>
</tbody>
</table>

Table 4-2. Summary of obscurant penetration results obtained at 100kHz PRF
5. SUMMARY & CONCLUSION

Test data have been collected in controlled clear conditions to validate the multi-returns detection and estimate the spatial resolution. For most cases the OPAL-P500 LiDAR was able to detect returns from the mesh screens and the target at the back of the chamber. Detection of the sixth screen and target was not possible when the mesh screens were at 1m interval separation. The cause is likely related to a lower transmission of the pulse when the beam size is small relative to the strands of the meshes. The transmission through the meshes as a function of the beam size should be measured in future tests. The collected data also confirmed that the spatial resolution of the OPAL-P500 for objects illuminated by the same beam falls somewhere between 0.5m and 1m; the theoretical limit is 0.6m based on the 4ns pulse used by the OPAL-P500.

Obscurants penetration measurements were also performed using ARD and water fog in controlled conditions. Results obtained using a PRF of 25kHz indicate that a target of reflectivity of ~75% can be detected through 24m of obscurants corresponding to an extinction coefficient per meter of ~0.15m⁻¹. When a target of reflectivity of ~5% is used, it can be detected at an extinction coefficient per meter of ~0.10m⁻¹. The results were similar for both the ARD and the water fog, indicating that both obscurants had similar scattering efficiency in the conditions used for the aerosol chamber tests.

The obscurant penetration performances were also independently validated by using the LiDAR equation, along with the parameters of the OPAL-P500 LiDAR, to predict the thickness of the obscurants cloud. Considering uncertainties such as the actual reflectivities of the targets, differences between pulse travel directions and the transmissometer alignment, the predictions are coming close to an expected value of ~24m.

Future work will include additional estimates the spatial resolution when subjected to the presence of obscurants. Additional obscurants penetration tests will also be performed with the OPAL LiDAR equipped with a higher power laser.

6. ACKNOWLEDGMENTS

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7. REFERENCES


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