Characterization of the OPAL LiDAR under controlled obscurant conditions
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ABSTRACT
Neptec Technologies’ OPAL-120 3D LiDAR is optimized for obscurant penetration. The OPAL-120 uses a scanning mechanism based on the Risley prism pair. The scan patterns are created by rotating two prisms under independent motor control. The geometry and material properties of the prisms define the conical field-of-view of the sensor, which can be built to between 60 to 120 degrees. The OPAL-120 was recently evaluated using a controlled obscurant chamber capable of generating clouds of obscurants over a depth of 22m. Obscurants used in this investigation include: Arizona road dust, water fog, and fog-oil. The obscurant cloud optical densities were monitored with a transmissometer. Optical depths values ranged from an upper value of 6 and progressively decreased to 0. Targets were positioned at the back of the obscurant chamber at a distance of 60m from the LiDAR. The targets are made of a foreground array of equally spaced painted wood stripes in front of a solid background. Reflectivity contrasts were achieved with foreground/background combinations of white/white, white/black and black/white. Data analysis will be presented on the effect of optical densities on range and cross-range resolution, and accuracy. The analysis includes the combinations of all obscurant types and target reflectivity contrasts.

Keywords: DVE, LiDAR, Obscurants Penetration

1. INTRODUCTION
Helicopter pilots can encounter situations of Degraded Visual Environments (DVE) when they land or take-off in the presence of obscurants such as dust, snow, fog, and smoke. Under these conditions, pilots cannot see nearby objects that provide the visual references necessary to control the aircraft near the ground. There are many reported rotary wing accidents and maintenance costs due to brownout1.

Several sensing technologies have been evaluated to improve pilot situational awareness in DVE2. Millimeter-wave radar (MMW) can penetrate obscurants well due to their long wavelength but are limited in their spatial resolution capability. LiDAR have shorter penetration depths when compared to MMW radars, but can offer higher spatial resolution sufficient to detect small threats to the aircraft, such as wires, terrain depressions in the landing zone and small size objects lying in the landing zone3,4,5,6. A more in-depth characterization of the OPAL sensor was required to determine the expected resolution of small objects detection under conditions of obscurants.

This evaluation was done as part of a project with Defence Research and Development Canada – Valcartier (DRDC-V) with the objective of testing the OPAL 2.0 LiDAR under controlled conditions using the DRDC Valcartier aerosol chamber to quantify the effect of dense aerosol on single beam range and cross-range measurements accuracy and resolution.

2. OPAL LIDAR OVERVIEW
The Neptec Technologies’ OPAL LiDAR is a Time-Of-Flight based LiDAR that scans the environment using a pair of Risley prisms. The OPAL LiDAR has been developed in view of providing a true see-through capability for pilots in the final approach of a landing zone (LZ). The technical approach rests on a high power pulsed laser emitter combined with a sensitive receiver, a capability to extract target signals engulfed in a cloud of obscurants through a real-time exploitation of the waveform returns characteristics and an efficient filtering of noise caused by the reflection of light on particulate matter suspended in the air.

The OPAL-120 LiDAR, shown in Figure 2-1, is designed with a conical field-of-view (FOV) that can be built to be as large as 120°. The OPAL-120 is of special interest for airborne applications that require high data point density within a reasonably large FOV. Using the Risley prism pair scanning method; the sensor generates unique non-overlapping scan patterns that produce very dense 3D images with acquisition speeds of up to 200kHz point repetition frequency (PRF).
3. SETUP FOR CONTROLLED AEROSOLS TESTS

Figure 2-1 shows on the right side a picture of the DRDC-V aerosol chamber that is used for controlled tests in obscurants. The chamber is 22m long with a 2.4m x 2.4m cross-section. It has collapsible doors at both ends that are remotely activated. The obscurants are injected through high pressure nozzles; a set of ventilators is used to keep the obscurant particle distribution as uniform as possible.

Three types of obscursants were used for the tests: Arizona Road Dust (ARD), water fog, and fog oil. The obscurants are disseminated using mixing fans with both doors closed. The initial density or optical depth of the aerosols inside the chamber was controlled by the amount of the aerosols disseminated. After the dissemination of aerosols is completed, the front door of the chamber is dropped down to allow the LiDAR to perform the scans while the aerosols dissipate. The time for the aerosol dissipation inside the chamber depends on the wind direction. If the wind is in the direction of pushing aerosols inside the chamber, then it takes a longer time to dissipate. Once the targets inside the chamber are clearly observed and most aerosols are dissipated, the back door is opened to let the residual aerosols inside the chamber to be fully blown out of the chamber. For each experiment, transmissometers operating at wavelengths of 532 nm and 1600 nm are used to measure the transmission from a light source at one end corner of the chamber to the transmissometers detectors.

Figure 3-1 shows how the test targets were mounted in the obscurant chamber. The targets are made of a top and bottom sets of painted wood stripes (A) that are either black or white; the stripes are positioned in front of a back painted board (B) that can be also either black or white. Three front-back combinations were tested. They are black-on-white (BoW), meaning that the front stripes are black and the back target is white; white-on-black (WoB) and white-on-white (WoW). The angle between the front and back target is approximately 30°. Each front wood stripe has a thickness of about 1cm and a width of 10cm.
Once the chamber is filled with obscurants, the front door opens and the data is acquired with an OPAL-120 using 200kHz PRF. The OPAL operates at a wavelength of 1550nm. At the same time, a transmissometer acquires independent transmission data. Both data sets are time-stamped, allowing the correlation of the LiDAR data with the transmission data. The tests were done using a low average laser power of 33mW. The sensor is positioned at 60m from the target. The targets are positioned at back of the chamber, about 20m away from the front door. Therefore, the LiDAR goes through 40m of clear conditions and about 20m of obscurant cloud prior to hitting the targets. The laser pulses have a full angle divergence of 0.6mrad, producing a beam size of 3.6cm on the target surfaces.

4. TESTS DATA EXAMPLES

4.1 Tests in Arizona Road Dust (ARD)

Figure 4-1 shows an example of data obtained in ARD obscurant when operating at a PRF of 200kHz using the WoW targets. The left side shows the frontal view of the detection of the targets on the X-Y (cross-range / elevation) plane plane; the color map represents the range (along the Z axis), typically between 59.4 and 60.6m. The right side of the figure shows the X-Z (elevation / range) plane; the color map represents the intensity of the detections. The round-way OD corresponding to each scan number is also given, based on the transmissometer value measured at the time the scan was acquired. The indicated values are the one measured at 532nm, corresponding more closely to human eye visibility.

Figure 4-2 shows results for the WoB targets obtained in similar conditions. In this instance it can be seen that the back panel being black is not detected at the OD values listed in the figures.

4.2 Tests in Water Fog

Figure 4-3 shows an example of data obtained through a water fog obscurant when operating at a PRF of 200kHz, for the WoW targets. Figure 4-4 shows the corresponding data for the case of the WoB targets.

4.3 Tests in Fog Oil

Figure 4-5 shows an example of the detected LiDAR returns using the WoW targets immersed in fog oil obscurant. It can be noticed that due the small size of the fog oil particles (<0.5µm), the targets can be detected at much higher OD when compared to ARD or water fog.
Figure 4-1. Front and side view images of the WoW 3D target detection through ARD dust at rate of 200 kHz.
Figure 4-2. Front and side view images of the WoB 3D target detection through ARD dust at a rate of 200 kHz.
Figure 4.3. Front and side view images of the WoW 3D target based on range and intensity detection through water fog at a laser repetition rate of 200 kHz and heavy dust mode.
Scan 3, OD = 1.48

Scan 15, OD = 0.67

Scan 18, OD = 0.57

Figure 4-4. Front and side view Images of the WoB 3D target based on intensity detection through water fog at a laser repetition rate of 200 kHz. Each scan represents a 3-second scan.
Figure 4-5. Front and side view images of detections of the WoW 3D target based on range and intensity detection respectively through fog oil at 200 kHz.
5. RESULTS ANALYSIS

5.1 Attenuation versus Obscurant Type

Table 5-1 summarizes the comparative penetration capability as a function of the obscurant type. For the cases of the ARD and water fog, the values of OD (roundtrip) represent the OD threshold at which the OPAL starts to detect the targets. For the fog oil, the targets were already detected at the first scan, even at the very low laser average power. This is the easiest obscurant to penetrate due to the small size of the particles relative to the laser wavelength.

In the case of the WoW targets, the detection of the white strips in front happens at a lower OD when compared to the back white panel because the angle of incidence of the beam is 30° relative to the normal of the front wood strips surface. For the WoW and WoB targets, the detection in the ARD happens at the higher ODs when compared to water fog; the water fog is therefore more difficult to penetrate. For the BoW, the reverse happens; it is potentially only caused by fluctuations in the obscurant dispersion. The column of obscurants seen by the transmissometer may differ from the one traversed by the laser pulses. Also, the OD estimates below assume a uniformly distributed cloud of obscurants; in reality the uniformity of the obscurant particles distribution is not a parameter under control.

<table>
<thead>
<tr>
<th>Aerosol</th>
<th>Freq (kHz)</th>
<th>Target</th>
<th>WoW Front</th>
<th>WoW Back</th>
<th>WoB Front</th>
<th>WoB Back</th>
<th>BoW Front</th>
<th>BoW Back</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARD</td>
<td>200</td>
<td>OD</td>
<td>1.87</td>
<td>3.03</td>
<td>2.29</td>
<td>0.76</td>
<td>-</td>
<td>&lt;= 1.17</td>
</tr>
<tr>
<td>Fog Oil</td>
<td>200</td>
<td>OD</td>
<td>&gt; 8.24</td>
<td>&gt; 8.24</td>
<td>&gt; 6.35</td>
<td>&gt; 6.35</td>
<td>-</td>
<td>&gt; 8.84</td>
</tr>
<tr>
<td>Water fog</td>
<td>200</td>
<td>OD</td>
<td>1.55</td>
<td>1.97</td>
<td>1.16</td>
<td>0.67</td>
<td>-</td>
<td>&lt;= 1.45</td>
</tr>
</tbody>
</table>

Table 5-1. Maximum optical depth (round-way) for 3d targets to be detected at distance of 60 m with obscurant cloud. ‘≤’ means the target starts being detected at the value, while > means the target was detected right at the beginning of the scan.

5.2 Impact of Multi-Scattering on Accuracy and Resolution

Cross-Range resolution:
The detection of the front targets (X-Y plane) as shown in Figure 4-1 to Figure 4-5 clearly demonstrates an excellent cross-range resolution in the detection of the frontal wood strips location against the background plane. The edges of all wood strips are very well defined. This result holds for all OD values and types of obscurants tested. The cross-range resolution in the presence of obscurants compares with the cross-range resolution in clear conditions.

Range Resolution:
The theoretical range resolution for the sensor is about 60cm, based on its pulse width of ~4ns, for two objects located in a single beam. The experiments have confirmed that value. This can be seen for the case on WoW by looking at the side view for small OD values, such as OD=0.46 for ARD in Figure 4-1, OD=0.39 in Figure 4-3, and OD=0.19 in Figure 4-5. In the top half of the side view point cloud, there are several data points distributed between the slanted white wood strips and the back white panel. The separation in the top half between the two structures is at a maximum of about 50cm. Beams will partially hit the slanted wood strips and partially hit the back panel. The received signal will not be able to resolve those reflections from the same beam and, depending upon how the beam is split, the detection will be determined somewhere in the middle. It can also be seen that when the separation between the objects increases beyond 50cm, such as in the bottom half of the target structure, there are no more data points in between the back and the front objects and they become properly resolved.

Range Accuracy & Measurement Uncertainty:
Figure 5-1 and Figure 5-2 show examples of range measurements and associated standard deviation versus the obscurant OD value for the WoW back target through ARD and water fog obscurants, respectively. As the OD increases, the range of the target is slightly reduced, by about 12-14-cm for an increase of ~2 OD. In those examples, the detection is performed on the falling edge of the last pulse and because the walk calibration of the sensor is not optimal when
receiving very low amplitude signals, it explains the shortening of the measured range as the signal intensity decreases with larger OD values.

On the other hand, it can be observed that the measurements standard deviations tend to be reduced with increasing OD. The examples in the graphs below show standard deviation moving from ~4cm to 2.5cm with an increase of ~2 OD. At larger OD values, only the beams that fully hit the back target are detected, thus the detected back target ranges are close to each other and it lowers the standard deviation. However, at lower OD values, edge effects will be more prominent, with beams partially hitting the front target and the back target. The return amplitude of those signals will be lower (because the beam is split) and due to some limitation of the walk calibration, the associated range appears a bit closer than it should be. This can be seen from the side views at low ODs, where the noise is mostly located in front of the back panel, due to a shorter estimated range.

Figure 5-1. Range and standard deviation measurements for the WoW back target vs OD in ARD obscurant

Figure 5-2. Range and standard deviation measurements for the WoW back target vs OD in water fog obscurant
6. SUMMARY & CONCLUSION
The main objective of this study was to determine the impact of the presence of obscurants on range and cross-range measurements accuracy and resolution. The study was done with a low power LiDAR given that the objective was not to establish absolute maximum penetration in obscurants. In summary, the results indicate that at 1.5\( \mu \)m wavelength obscurants made of fog oil, ARD, and water fog will present an increasing order of difficulty for their penetration. The cross-range resolution and the range resolution in the presence of obscurants do not have a strong dependence on the obscurant density and compare with what is observed in clear conditions. Due to a non-optimal calibration for range measurements made using the falling edge of the last pulse mode, the absolute ranging estimates were up to 14cm shorter in high density obscurants. The range measurement’s standard deviation at a given OD value was found to be between 2.5 - 4.0cm, with the lower value happening at larger OD values. This counter-intuitive result happens because the data dispersion due to edge effects is lessened at larger obscurant density values.

7. ACKNOWLEDGMENTS
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8. REFERENCES


