Mapping of ice, snow and water using aircraft-mounted LiDAR
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ABSTRACT
Neptec Technologies Corp. has developed a family of obscurant-penetrating 3D laser scanners (OPAL 2.0) that are being adapted for airborne platforms for operations in Degraded Visual Environments (DVE). The OPAL uses a scanning mechanism based on the Risley prism pair. Data acquisition rates can go as high as 200kHz for ranges within 240m and 25kHz for ranges exceeding 240m. The scan patterns are created by rotating two prisms under independent motor control producing a conical Field-Of-View (FOV). An OPAL laser scanner with 90° FOV was installed on a Navajo aircraft, looking down through an aperture in the aircraft floor. The rotation speeds of the Risley prisms were selected to optimize a uniformity of the data samples distribution on the ground. Flight patterns simulating a landing approach over snow and ice in an unprepared Arctic environment were also performed to evaluate the capability of the OPAL LiDAR to map snow and ice elevation distribution in real-time and highlight potential obstacles. Data was also collected to evaluate the detection of wires when flying over water, snow and ice. Main results and conclusions obtained from the flight data analysis are presented.

Keywords: Flight Test, LiDAR, Snow, Ice, Water

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 poor visibility leading to lack of situational awareness for pilots.

However, the lack of visual cues even in good visibility conditions can also lead to fatal accidents. In an environment such as the Arctic it can at times be difficult to discriminate between the icy/snowy ground, the water and the sky because of lack of visual contrasts. On 9 September 2013, a Canadian Coast Guard helicopter, operating from the vessel Amundsen on an ice reconnaissance mission in the M'Clure Strait north of Banks Island, Northwest Territories, struck the water and sank. The three persons on board were fatally injured. The fatal Coast Guard helicopter crash in the Arctic Ocean was likely due to a lack of visual cues to judge altitude while flying low over open water, according to a report released by the Transportation Safety Board.

Several sensing technologies have been evaluated to improve pilot situational awareness in DVE. Millimeter-wave radar (MMW) can penetrate obscurants well due to their long wavelength but are limited in their spatial resolution capability. LiDARs 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 zone. Other optical technologies, such as infrared cameras and Flash LADAR have also been evaluated for this purpose.

This paper reports on a flight trial where an OPAL LiDAR is mounted on a fixed wing aircraft flying over snow, ice and water, simulating a landing approach. The work was done to identify answers to the question of the usefulness of LiDAR acquired 3D data to augment the pilot situational awareness when flying in environments such as the Arctic.

2. SENSOR CHARACTERISTICS

The OPAL LiDAR was originally 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 LiDAR developed by Neptec has been subjected to several field evaluations to test its penetration capabilities in a variety of obscurant conditions. Its performance in terms of obscurant penetration was described in a previous publication. The flight tests were done with the OPAL-120 LiDAR, shown in Figure 1. The LiDAR is designed with a conical field-of-view (FOV) that could be set as high as 120°; a 90° FOV was used for the tests discussed herein.

The OPAL-120 is of special interest for airborne applications that require high data point density within a reasonably large FOV. The scanning mechanism is based on the Risley prism pair principle; 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). Table 1 lists the main parameters of the OPAL-120 used for the flight tests.

![Figure 1. OPAL-120 LiDAR with conical FOV projection.](image)

<table>
<thead>
<tr>
<th>Laser Wavelength</th>
<th>1540nm</th>
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<tbody>
<tr>
<td>Pulse Repetition Frequency PRF (maximum)</td>
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</tr>
<tr>
<td>Field-Of-View (conical)</td>
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</tr>
<tr>
<td>Effective PRF at short range</td>
<td>200kHz @ up to 240m</td>
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<tr>
<td>Average Laser Power</td>
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<td>Beam Divergence</td>
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<tr>
<td>Size</td>
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</tr>
<tr>
<td>Weight</td>
<td>24kg</td>
</tr>
<tr>
<td>Power</td>
<td>&lt;120W, 12-32V</td>
</tr>
<tr>
<td>Operating Temperature (storage temperature)</td>
<td>-40° to +65° C (-40° to +85°C)</td>
</tr>
</tbody>
</table>

Table 1. Main parameters of the OPAL-120 LiDAR used for the flight tests.

### 3. AIRCRAFT INSTALLATION

The tests were done with a Navajo fixed wing aircraft as shown on the left side of Figure 2. The right side shows how the sensor pod is installed. It looks directly downward through a hole in the aircraft floor. The sensor pod includes the OPAL-120, a light polarized LiDAR and navigation sensors. The data acquired by the LiDARs are geo-referenced using the navigation data.
4. OPTIMAL SCAN PATTERNS & DATA DENSITY FOR THE OPAL-120

4.1 Optimal Scan Patterns

The OPAL-120 LiDAR generates scan patterns by bending a laser beam through a pair of Risley prisms under independent motor control. The speed ratio of the motors will define unique scan patterns. It is important to determine which motor speed ratios are the most optimal in scanning the environment. A Figure of Merit (FOM) was developed in view of identifying optimal motor speed ratios presenting the following capabilities:

- Generation of data with a good uniform distribution. This means avoiding motor speed ratios that will leave large gaps in the data sets. An example is presented in Figure 3 where the pattern on the left offers good data distribution uniformity whereas the pattern on the right leaves important gaps in the data distribution. Both patterns are acquired for duration of 2 seconds.
- Generation of scan patterns that will rapidly fill the gaps over time, as opposed to repeating the same patterns.
- Robustness to small motor speed fluctuations. The scan patterns shown in Figure 3 are examples of a bad motor speed ratio selection. Although it produces a uniform data distribution at a motor speed ratio of 9.24 (left side), a small variation of the motor speed ratio will produce scan patterns with significant gaps as shown on the right side of the figure where the scan pattern corresponds to a motor speed ratio of 9.25.
- Generation of patterns that offers a reasonable uniformity in the data distribution for both static and dynamic platforms.

Figure 3. Example of a well distributed coverage (left) and a coverage with significant gaps (right) both acquired over a period of 2 seconds with respective motor speed ratios of 9.24 and 9.25.
Using the FOM function, some optimal scan patterns were identified, fulfilling the criteria identified above. An example of optimal scan pattern is given in Figure 4, where the coverage is shown for periods of 12ms and 1s, respectively.

Figure 4. Example of an optimal scan pattern coverage after a 12ms period (left) and a 1s period (right).

4.2 Data Density Distribution

An interesting property of the scans generated by a Risley prisms pair is that the data density as a function of the radial position in the FOV presents a constant profile independent of the speed ratio of the prisms motors, of the data acquisition rate and of the data acquisition duration. Figure 5 shows an example of the data density distribution (data points/m²) as a function of the radial position in the FOV, obtained for data acquired with a 90 degrees FOV over a period of 10 seconds, at a PRF of 200kHz and a standoff distance of 200m. While the data density profile is invariant, its amplitude has to be normalized to the situation at hand. For example, the normalization is linear with the acquisition time and acquisition rate and will depend on the inverse of the square of the distance.

Figure 5. Data density versus distance from center of FOV for 10 seconds acquisition time at 200kHz PRF, 90° FOV, and at a standoff distance of 200m.
5. FLIGHT DATA RESULTS

5.1 Simulated Landing

The flight tests were performed along the St-Lawrence River which flows just slightly west of Quebec City. Figure 6 shows a picture of the stretch of land below the aircraft. It includes open water, chunks of ice, a mix of ice chunks and snow and the snowy terrain corresponding to the cliff. The flight simulated a landing approach. The aircraft went progressively down from an altitude of about 70m to a low altitude of 12m. The average speed of the aircraft as it slowed down was about 43m/s (155km/hr). The data was acquired at a rate of 200kHz with a 90° FOV.

Using the aircraft initial altitude of 70m and speed of 155km/hr along with the LiDAR parameters (90° FOV, 200kHz PRF), Figure 7 shows the expected scan patterns projected on the ground over a period of 10 seconds. The red arrow indicates the direction of motion of the aircraft. The scan pattern’s extent from the center line of travel is a result of the FOV and the aircraft altitude; in this situation, it corresponds to about 70m on each side of the center line of travel. Figure 8 shows the corresponding data density on the ground at the start altitude of 70m (red line) and at the end altitude of 12m (blue line). It can be seen that the data density rises significantly as the aircraft reaches its low altitude of 12m while the extent of the data coverage on the ground narrows down correspondingly.

The left side of Figure 9 shows raw LiDAR data over a segment of the aircraft travel. Most of the returns are from a mix of snow and ice chunks directly below the aircraft, close to the shore of the river. The data points are colour-coded in accordance to their elevation, blue being the tallest elevation at around 1.5m over that stretch. The terrain leading to the cliff has higher elevation and can be clearly seen in blue. The right side of Figure 9 shows the raw data assigned to a regular 1m² grid for better ease of viewing.

Figure 10 presents a grid view corresponding to the tail end of the flight travel where the 3D data points are mapped to a 1m² grid. The variations in terrain elevation can be clearly seen through the colour-coded data. For example, two chunks of ice are clearly represented in the foreground; it is difficult to assess the importance of their elevations just by looking at their 2D pictures on the right side. A small pier can also be immediately seen in the background, presenting a higher elevation.

![Figure 6. Picture showing the stretch of ground being mapped with the OPAL LiDAR. It includes water, chunks of ice, snow, and the cliff on the left side of the direction of travel.](image-url)
Figure 7. Ground data distribution at a height of 70m with the aircraft moving at 155km/hr, using a 90° FOV and a 200kHz PRF. Arrow indicates direction of motion.

Figure 8. Data density in points/m² versus the distance from the center line of motion. This is given for an aircraft moving at a speed of 155km/hr comparing the data density for an altitude of 12m (blue line) and an altitude of 70m (red line).
Figure 9. Raw LiDAR data are shown on the left side. The right side shows the same data assigned to a 1m² grid. The data is colour-coded in accordance to the terrain elevation as per the legend on the top right.

Figure 10. OPAL LiDAR data collected along the stretch of land under the aircraft and assigned to a 1m² grid. Terrain elevations are colour-coded as per the legend on the top right.
5.2 Ice versus Water

LiDAR data was also collected with the aircraft flying at 285m over the water level and looking down at high power transmission lines stretching over the St-Lawrence River. The distance between the aircraft and the wires did vary and was about 95m at its closest point. The raw LiDAR data, acquired at a PRF of 25kHz, are shown at the left side in Figure 11, while the corresponding picture taken from the cockpit is shown on the right side. Although the original objective of the test was the detection of the wires, the data indicates an interesting demarcation between water and ice in the extent of the light pulses returns detected relative to the center line of motion. This can be seen by comparing the delineation between water an ice as seen in the corresponding 2D image with the raw LiDAR data showing the same delineation along the direction of travel.

On the basis of that data set, we can conclude that ice can be less reflective than water. Further studies would be of interest to better characterize and quantify this difference. LiDAR may have potential to identify the presence of ice chunks in a body of water.

Figure 11. Raw LiDAR data from aircraft flying over the St-Lawrence river (left) showing a net demarcation between water and ice. The corresponding camera image is shown on the right showing the delineation between water and ice.

5 CONCLUSION

The paper summarizes the results of flight tests simulating a landing approach over a land surface covered with a mix of water, ice chunks and snow. The raw 3D data were acquired and mapped into a 1 m² grid, easily showing the variations in terrain elevation due to ice chunks and other objects. The tests were done, in part, to assess the potential contribution of a 3D LiDAR to augment a pilot situational awareness while attempting to land in an unprepared area in the Arctic. Although further tests are required to characterize and quantify the benefits, it is clear from these early tests that a 3D LiDAR brings situational awareness benefits when operating in conditions of poor visibility contrasts such as the conditions often encountered in the Arctic. The test data also indicate a possibility to differentiate between ice and water using a LiDAR and more research is required in that area.
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7 REFERENCES