MITIGATING THE IMPACT OF THE LASER FOOTPRINT SIZE 
ON AIRBORNE LIDAR DATA ACCURACY

R.Valerie Ussyshkin, Technology Group Manager, Airborne Survey Products 
Rachana Ravi, Technical Analyst 
Michael Ilnicki, System Scientist 
Martin Pokorny, Technical Analyst 
Optech Incorporated, 300 Interchange Way 
Vaughan, Ontario, Canada L4K 5Z8
valerieu@optech.ca 
rachanar@optech.ca 
michaeli@optech.ca 
martinp@optech.ca

ABSTRACT

Airborne lidar technology is demonstrating outstanding results in generating high-accuracy spatial data for a wide range of terrestrial mapping applications. However, the data quality and accuracy achievable in real survey conditions depend on many different factors. The laser footprint size plays a crucial role in both the vertical and horizontal accuracy of the data collected over sloped or non-uniform terrain, as well as in the horizontal accuracy of break-lines. This study explores the application aspects of the interaction of the laser beam with sloped surfaces of a non-uniform terrain. It also suggests a new approach to mitigate the negative impact of the finite laser beam footprint size on airborne lidar data quality. The new approach will help lidar system users to maintain reasonable data accuracy regardless of the size of the footprint and the slope of the terrain. The data for this study was collected using airborne lidar equipment manufactured by Optech Incorporated.

INTRODUCTION

Conventional consideration of an airborne lidar system’s error budget includes the errors coming from the main subsystems, laser rangefinder and geo-positioning system (Airborne 1, 2001). Further errors might be added due to the misalignment and/or time synchronization between these subsystems as well as those introduced during data processing and digital terrain model (DTM) production (Ussyshkin and Smith, 2006, Maas, 2003). Scanning geometry and interaction of the laser beam with different types of targets may have a significant influence on measurement accuracy for airborne (and terrestrial) laser scanning systems, but for various reasons, it is rarely considered to be a part of the error budget (Ussyshkin et al., 2007; Pfeiffer and Briese, 2007). While characterizing lidar instrument performance and final data accuracy, every manufacturer uses their own methodology, which is often developed for a reference set of operational and environmental conditions so that the impact of the scanning geometry on the resulting data accuracy specifications is minimized. For example, some manufacturers choose a reduced scan angle to minimize the negative impact of scanning geometry on the data accuracy. However, due to the nature of lidar data collection, there are many other factors which may—and usually do—affect data accuracy achievable in the field. Translating the specification sheet accuracy numbers to real world achievable accuracy is a challenge usually left to the end user (Ussyshkin and Boba, 2008).

Some studies suggested empirical methodologies for lidar data accuracy assessment in moderately sloped terrain and different types of vegetation (Hogdson and Bresnahan, (2004) and references therein). Another methodology to assess and improve the accuracy of lidar data collected over mountainous terrain suggests the use of lidar-specific targets as control points (Hogarty et al., 2007). A different approach to estimate the range error in lidar measurements over steep terrain, based on waveform analysis, has been reported by Martin (2005) where the recorded pulse waveform has been compared with a simulated one, and the differences in RMS and standard deviation have been estimated.

A new methodology based on quantitative estimation of the measurement error due to scanning geometry using only measured laser points has been proposed by Schaer and coauthors (Schaer et al., 2007). The local terrain
normal was calculated by applying a specially developed algorithm and calculating eigenvalues of a covariance matrix of the surrounding points. This knowledge of the terrain normal provides the usually missing link connecting the change in the laser footprint size as a function of the beam divergence, flying altitude and angle of incidence (AOI). Adding this information to the error propagation model results in the introduction of a quality factor, which could be added to the DTM production cycle and support automated classification of lidar data.

In this paper we describe a new approach to reduce the negative impact of scanning geometry on variations in the rangefinder error. The new approach does not require a priori knowledge of the terrain slope, but it is based on the information found only in collected lidar data. The range measurement error caused by scanning geometry for every laser shot is reduced by applying a correction factor, which is calculated for every laser shot based on recorded range measurements of the surrounding points and the geo-positioning data. The proposed approach was tested for a limited set of operational conditions, but could potentially be applied to data collected over mountainous terrain, where mitigating the footprint error is most critical.

**LASER BEAM – TARGET INTERACTION**

The combined effect of a finite laser footprint size and variations on the angle of incidence (AOI) due to large scan angles or sloped highly non-uniform terrain (Figure 1) may result in strongly variable accuracy of the range measurements for every laser point (Ussyshkin et al., 2009). Traditionally, rangefinder accuracy is considered to be dependent on system characteristics, which in turn, determine characteristics of the emitted and return pulses, including pulse width and energy, noise, detector sensitivity, etc. (Baltsavias, 1999). However, little consideration is usually given to the scanning geometry, which in fact, may contribute significantly to the variations in range measurement accuracy. The magnitude of these variations is linked not only to the known scan angle and footprint size on the ground, but also to variable and a priori unknown terrain slope, and the ground reflective properties, which makes accuracy assessment particularly difficult (Schaer et al., 2007 and Hodgson and Bresnahan, 2004).

![Figure 1. Scanning geometry introduces variable error into range measurements in sloped terrain (a) and wide scan angles (b).](image)

The laser footprint size on the ground $A_L$, typically referred to in the literature as $1/e^2$ or $1/e$ diameter, could be estimated using a basic mathematical relationship connecting flying height, $h$ and laser beam divergence, $\delta$ (Baltsavias, 1999):

$$A_L = 2h \tan(\delta/2) \quad \text{or} \quad A_L = h\delta$$

This mathematical relation is valid only for normal incidence of the laser beam with respect to the target (ground). While collecting data, the AOI of the laser beam is continuously changing due to changing scan angle (known and predictable) and terrain slope (unknown and unpredictable). The combined effect of these changes...
results in the elongation of the laser footprint on the ground (Figure 1), both in cross-track (y) and along-track (x) directions. The magnitude of this elongation would be proportional to the AOI. Considering uncertainty in the horizontal position of the measured laser point due to the finite size of the laser footprint on the ground as an error dependent on laser beam divergence, flying height and scanning geometry determined by scan angle and terrain slope, one could estimate the value of this error for various operational conditions and terrain slopes. This error may become a significant part of the overall lidar error budget at large scan angles even in the case of flat uniform terrain (Ussyshkin, 2008), but it obviously becomes critical for highly non-uniform terrain in mountainous areas, where steep slopes cause large AOI resulting in increased horizontal and vertical errors (Schaer et al., 2007).

The simplified geometry presented in Figure 1 becomes more complicated if an actual laser pulse power distribution within the waveform is taken into account. For the most typical types of lasers used in commercial airborne lidar systems (Optech’s ALTM Gemini and Orion systems), power distribution of the emitted laser pulse can be approximated by Gaussian distribution (Figure 2).

Figure 2. Power distribution within the waveform of the emitted laser pulse can be approximated by a Gaussian distribution of the laser used in Optech’s ALTM Gemini and Orion systems.

If the target plane is non-orthogonal with respect to the incident laser beam, spatial and temporal characteristics of the reflected pulse might be distorted, depending on variations of the physical properties of the target, or in the simplest case, just broadened. Moreover, the actual location of the power peak, or another threshold point at the pulse front, which would trigger the rangefinder electronics is, generally speaking, unknown. It has been reported that for flat slanted targets, the lidar ranges are shorter than they are supposed to be for the beam center (Jutzi and Stilla 2003). Based on this observation, one could suggest that a lidar system would take the range measurements before the pulse reaches its maximum in the center of the laser footprint. In other words, in the case of slanted targets or sloped terrain, a lidar system would generate an unavoidable range measurement error, which would depend on the AOI, flying height and characteristics of the undistorted pulse. This error diminishes for short pulses, small AOI, and small beam footprint size (Pfeifer et al., 2007).

The range measurement error in lidar data and consequent vertical and horizontal errors due to laser pulse broadening/footprint elongation as a function of AOI have been modeled using the Gaussian approximation for the laser pulse power distribution (Ilnicki, 2008). Figure 3 illustrates the concept used in this modeling for flat uniform terrain and wide scan angles, where a simplified two-dimensional concept could be considered, and the local terrain normal in the vertical plane is constant, while the AOI is simply equal to the scan angle (Figure 1b).
Figure 3. Pulse broadening effect in flat uniform terrain, 1 km flying height and scan angles close to ±30°.

In real-world survey conditions, the local terrain normal is changing its orientation with every laser shot, and is a priori unknown. When adjacent flight lines are flown over highly variable terrain the laser footprint-related error can be observed in the overlap regions as disagreements between measured terrain locations. Figure 4 shows a terrain profile representing two fragments of two overlapping strips collected over strongly non-uniform terrain (mountainous area) where the magnitude of the range measurement error linked to the scanning geometry is changing during a straight and level flight and manifests itself in changing discrepancies in xyz-coordinates.

Thus, the range measurement error caused by the laser footprint error in lidar data collected over highly non-uniform terrain is not only strongly variable, but seems to be impossible to predict. That is why the only practical approach to mitigate this error has to be based on the calculation of the moving local terrain normal for every laser shot based on the lidar measurements. In the next section we describe a newly developed approach to mitigate this error along with its practical application.
**Figure 4.** Two fragments of a terrain profile of two overlapping strips collected over strongly non-uniform terrain (mountainous area). Discrepancies between two overlapping strips in each case indicate variability of the range measurement error linked to the scanning geometry.

**APPROACH AND APPLICATION**

The proposed approach to reduce the impact of the scanning geometry on range measurement accuracy is based on applying correction algorithms to raw range data so that the output from the data processing software has the footprint error reduced or eliminated. As the first step in this study we used a simplified two-dimensional consideration of the scanning geometry, which is applicable to the case of flat uniform terrain surveyed with wide scan angles close to ±30°. This consideration is often a valid assumption for real survey conditions since data collection missions are usually planned parallel to topographical contour lines and survey flight lines are best flown straight and level. For highly variable non-uniform terrain this assumption may or may not be valid, and a more sophisticated calculation based on three-dimensional modeling might be required.

Generally speaking, the data correction workflow should start with the classification or spatial discrimination of
laser points by applying a filter to remove all points lying above the ground so that the filtered output represents only bare-earth points. However, for the purpose of this study the classification step was replaced by selecting the last-return data to calculate the range correction factor, which is later applied to all range data. The instantaneous AOI for every laser shot could be calculated based on the automated analysis of $k$ number of neighboring laser points using the data recorded in the range file and the geo-positioning data recorded and processed by the navigation subsystem (POS/AV-510; POSPac 5.0). We used a simplified calculation based on the approach reported by Bae and Lichti (2004) to estimate the geometric curvature $M_{\text{curv}}$ of a point $p_i$ using the normal vectors $n$ of $k$ surrounding points:

$$M_{\text{curv}}(p_i) = k^{-1} \sum_{j=1}^{k} \|n_{p_i} - n_{\text{neighbor}(j,p_i)}\|$$

where $k$ is the size of the neighborhood, $n_{p_i}$ is the normal of point $p_i$ and $n_{\text{neighbor}(j,p_i)}$ is the normal of the $j$ neighborhood point of $p_i$.

We applied this approach to calculate the instantaneous terrain slope, $\beta_i$, and AOI for every laser shot using information in the range and SBET files. After calculating the AOI, the footprint correction factor was calculated for every laser shot using the model described in the previous section, and was applied to all recorded range data.

The proposed method has been applied to several datasets collected by ALTM Gemini and Orion systems during calibration flights over a control field, which could be considered as flat and uniform (airport runway). Since wide scan angles were used for most of the collected datasets, the footprint error at the edges of the scan is expected to be significant enough to be detected and corrected. Taking advantage of the dual beam divergence feature in the ALTM Gemini model, some of the datasets were collected with a wide beam divergence setting, which should have made the footprint error at the scan edges even more noticeable. Thus, for the purpose of this study, extreme scan angles and wide laser beam divergence settings were used to exaggerate the footprint error caused by large AOI, and flying heights typical for moderately non-uniform terrain surveyed with reduced scan angles at mid-altitudes.

Figure 5 shows an example of the calculated instantaneous terrain slope $\beta_i$ as a function of time over the control field for a small part of one of the datasets used in this study; it represents an intermediate step of the correction algorithm, which was graphed for quality control purposes. It shows that $\beta_i$ varies only within a few degrees over the scanned runway area. Nevertheless, due to the footprint elongation/pulse broadening effect at the scan edges for scan angles close to ±25-30°, the range measurement error should be noticeable.

![Variations of Instantaneous Terrain Slope $\beta_i$](image)

**Figure 5.** An example of the calculated instantaneous terrain slope $\beta_i$ as a function of time over the control field for a small part of one of the datasets used in this study.

**Figure 6** shows an example of two elevation profiles plotted against a control for the same dataset, while the range file of one of them has been modified by applying the footprint error correction algorithm. This example shows a noticeable difference in elevation at the scan edges, which is attributed to the error caused by the scanning geometry. The RMS error calculated for two datasets shows significant improvement for the corrected data.
Table 1 represents a comparison of elevation standard deviation and RMS from several datasets collected by ALTM Gemini and Orion systems. This comparison shows that the footprint error correction consistently and significantly improves accuracy for the datasets collected with wide scan angles and wide divergence settings. On the other hand, for narrow beam divergence and reduced scan angles, there are no noticeable differences in RMS error for corrected and original datasets, as expected.

Table 1. Comparison of RMS errors from datasets collected by ALTM Gemini and Orion systems, with and without correction of the error caused by the scanning geometry.

<table>
<thead>
<tr>
<th>Footprint error Correction</th>
<th>System</th>
<th>PRF×SF×SA – AGL*</th>
<th>Beam Divergence (mrad)</th>
<th>Strip</th>
<th>RMS (m)</th>
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<tbody>
<tr>
<td>OFF</td>
<td>Gemini-8</td>
<td>33×30×28-1200</td>
<td>0.8</td>
<td>16</td>
<td>0.111</td>
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<tr>
<td>ON</td>
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<td>16</td>
<td>0.055</td>
</tr>
<tr>
<td>OFF</td>
<td>Gemini-6</td>
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<td>0.3</td>
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<td>0.105</td>
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<tr>
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<td>11</td>
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<tr>
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<td>11</td>
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<td>13</td>
<td>0.131</td>
</tr>
</tbody>
</table>

*Pulse Repetition Frequency (kHz) × Scan Frequency (Hz) × Scan Angle (±°) – Above Ground Level (m)

As the next step in this study we plan to apply the newly developed approach to datasets collected over highly variable or mountainous terrain, and to verify the robustness of the developed algorithm and its applicability for data collected in real-world survey conditions. Another potential improvement to the proposed approach would require incorporation of intensity data, which contains information describing the power of each reflected laser.
pulse. This study examined the effects of a correction algorithm to reduce the effects of scanning geometry on ranging accuracies for level, flat and spectrally homogenous terrain. A further refinement to this correction would involve consideration of measured intensities (peak power of the return pulse) to better predict pulse shape and understand the effects of a broadened return pulse on ranging accuracy, which would potentially lead to a more sophisticated approach to correct the range measurement error linked to scanning geometry and beam-target interactions.

CONCLUSIONS

A new approach to mitigate the negative impact of laser footprint size on airborne lidar data accuracy was tested. The approach does not require a priori knowledge of terrain slope, and is based on calculating the correction factor for each range measurement using the data recorded by the laser scanner and position and orientation systems. The proposed approach was tested for a limited set of operational and environmental conditions. Significant and consistent improvement in data accuracy was demonstrated for the datasets, where correction for the error caused by scanning geometry had been applied. The new approach could potentially be used for improving accuracy of the lidar data collected over mountainous terrain, where mitigating the error linked to the terrain slope is the most critical.

REFERENCES

Airborne1, 2001. LiDAR Accuracy: An Airborne 1 Perspective, Airborne 1 Corporation, El Segundo, California, USA.