# PERFORMANCE CHARACTERIZATION OF AN AIRBORNE LIDAR SYSTEM: BRIDGING SYSTEM SPECIFICATIONS AND EXPECTED PERFORMANCE

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**KEY WORDS:** LIDAR, data acquisition, specifications, impact analysis, parameters, performance, accuracy, understanding

## ABSTRACT:

Airborne laser scanning, the preferred operational tool in remote sensing, surveying, and mapping, is demonstrating outstanding capabilities in generating high-accuracy spatial data with superior efficiency for a variety of applications. However, achieving results to fulfil survey project requirements demands a thorough understanding of the performance capabilities of the airborne surveying equipment being used. Due to the complexity of new technologies and the variability of factors affecting the quality of lidar-derived end products, certain performance characteristics presented by manufacturers on system specification sheets often look misleading. Moreover, the lack of widely accepted standards for lidar system characterization leaves room for variable interpretation of common terms and misinterpretation of instrument performance capabilities. This paper represents the efforts of Optech Incorporated, a leading manufacturer of airborne lidar systems, to bridge the gap among numbers on the system specification sheet, the achievable system performance in the field, and the expected quality of lidar-derived end products. We examine the main parameters characterizing airborne lidar system performance and provide technical information that usually remains out of scope of the system specification sheet but may significantly affect operational efficiency and achievable field performance. We also analyze the impact of various operational parameters and certain survey conditions, such as the highly variable reflectance of terrains, on lidar system performance. The demonstrated results should enable lidar service providers to avoid misinterpreting numbers on the specification sheets and bridge the gap between the manufacturers' approach to characterizing system capabilities and the expectations of lidar system end users.

## 1. INTRODUCTION

Airborne lidar technology offers an efficient way of generating high-accuracy spatial data collected with superior efficiency for a wide range of mapping and surveying applications. However, achieving results that would meet the requirements of any surveying project requires a thorough understanding of lidar performance capabilities. Lidar data providers typically consider client expectations and translate them to main project requirements (Figure 1):

- What is the coverage area? How large is it, and what are the properties of the terrain (such as coverage, slope, and elevation above sea level)?
- What are the lidar-derived products, and what accuracy and density of points are required?
- What is the time frame for completing the project?

Based on these requirements, the lidar data provider typically derives the following:

- Project schedule
- Operational scenarios for lidar data acquisition (mission planning)
- Production procedures
- Overall project cost.

Project success is determined by the ability of the lidar data provider to meet the customer's expectations while maintaining a cost-efficient lidar workflow through project and mission planning, data acquisition, processing, and production. In other words, the lidar data provider has to match lidar instrument capabilities to project requirements (Figure 1) to collect data of required and uncompromised quality and quantity while keeping the project cost as low as possible.

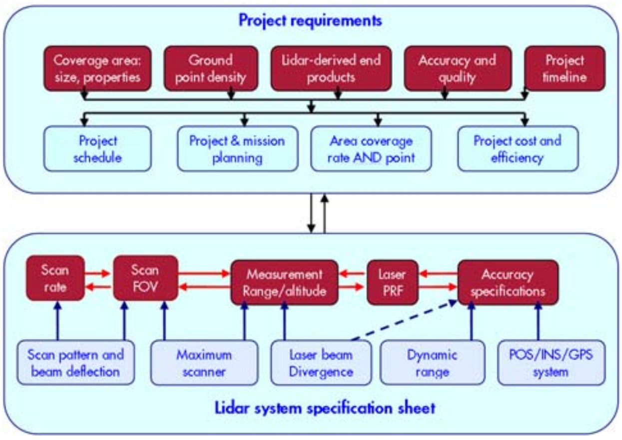

Figure 1. Matching performance characteristics from the lidar specification sheet to project requirements

On the other hand, lidar instrument manufacturers always try to represent system capabilities in the best possible way by presenting main performance characteristics, many of which may not be directly relevant to actual lidar project requirements. Many factors and technical details are often left out of the system performance specification sheet. That is why the "better" numbers on the lidar performance specification sheet do not always translate to better performance from the user's point of view. In real-life practice, a user's top priorities, typically data quality and project cost-efficiency, may or may not be directly fulfilled by the "better" numbers presented by the instrument manufacturer.

Moreover, owing to a lack of generally accepted guidelines for lidar performance characterization, lidar system manufacturers may choose different methodologies to characterize and to present system performance capabilities. That is why it is very important for the user of a commercial lidar system to understand the underlying technical premises behind values on a specification sheet and to make informed decisions to fulfil project requirements (Figure 1). This paper will help lidar system users to understand the underlying relationships among various numbers on an airborne lidar specification sheet and to bridge the gap between the "bare" numbers and the expected real-life performance capabilities of a lidar system.

## 2. DATA COLLECTION EFFICIENCY VERSUS PERFORMANCE SPECIFICATIONS

How fast can the system collect data? How quickly can the project be completed? In other words, how cost-efficient is the lidar system? Contrary to a mistaken assumption, the most cost-efficient approach is not simply to set every operating parameter of a lidar system to its maximum capacity. In fact, the operating parameter that contributes most pertinently to maintaining high density of points *and* achieving maximum area coverage rate is laser pulse repetition frequency (PRF). Because of its direct connection with data collection rate for achieving survey time cost-effectiveness, PRF has become a prime differentiating factor in the marketing of both lidar sensors and data collection services (Flood, 2001). However, considering PRF as a sole figure of merit without its connection to other lidar parameters can be misleading. We will describe how different mechanisms used for laser beam deflection and scan pattern may affect point density and area coverage rate and, hence, the operating parameters and cost-efficiency of a survey.

### 2.1 Link: PRF and Scan Patterns

Several scanning techniques, each with advantages and disadvantages, are employed in airborne lidar systems. The most common are (a) constant-velocity rotating polygon mirror and (b) oscillating mirror (Figure 2). The advantage of a rotating polygon mirror is its scan pattern, which appears as linear unidirectional and parallel scan lines on the target. However, its primary disadvantage is that for a certain period of time during each rotation cycle, range measurement is either not taken or, if taken, should then be discarded. As a result, with this type of scanning mechanism, laser PRF does not equate with data collection rate; hence, in most cases, manufacturers specify the PRF and data measurement rate separately.

The oscillating mirror scan mechanism seems to be more popular for airborne lidar systems. The mirror is always pointing to the ground, and the system's laser PRF is equivalent to its data collection rate. However, laser PRF does not immediately translate to area coverage rate for a given point spacing because two distinct oscillating scan patterns—sawtooth and sinusoidal—manifest two different laser point distribution outcomes (Figure 3). In a sawtooth scan pattern, scanner velocity is kept constant for most of the swath. This gives an almost uniform point distribution across the swath with slightly increasing point density towards the scan edges. In a sinusoidal scan, point density is the lowest at the centre of the swath and grows toward the edges of the scan line. That is why a lidar with a sinusoidal scan pattern has to operate at a much higher laser PRF to maintain the same nadir point density as a lidar with a sawtooth scan pattern. It was shown (Ussyshkin *et al.*, 2008b) that at a 1-km flying altitude, 30-Hz scan frequency, and ±25° scan angle, a lidar with a sinusoidal scan pattern has to operate at a 158-kHz PRF to achieve the same point density at nadir as a sawtooth scanner operating at 100 kHz.

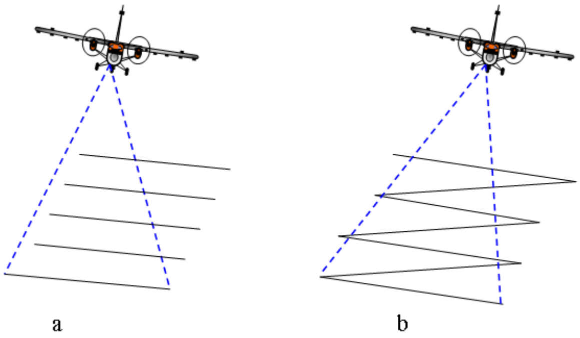

Figure 2. Scan patterns: (a) constant velocity rotating polygon mirror and (b) oscillating mirror

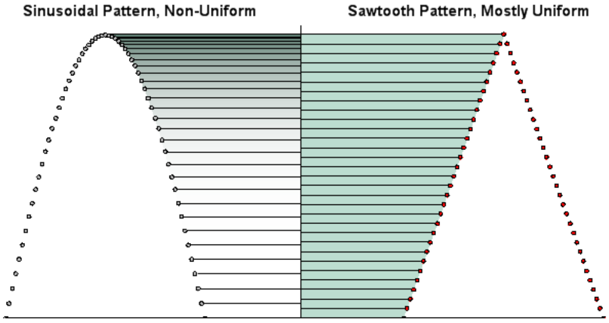

Figure 3. Sawtooth and sinusoidal scan patterns from an oscillating mirror scanner

Thus, from the user's point of view, laser PRF cannot be the only figure of merit for data collection efficiency since scan pattern significantly changes cross-track point distribution and affects one of the most important project requirements—ground point density. To meet project-required point density on the ground *and* to maximize area coverage rate, the lidar system user must carefully consider the choice of scan pattern along with laser PRF.

### 2.2 Link: Scan Frequency and Scan Angle

Maximum scan frequency, as specified on a lidar system specification sheet, is another very important instrument parameter that affects data collection efficiency achievable in the field. Again, comparing "bare" numbers of the maximum scan frequency may be quite misleading.

**Scan rate for rotating polygon mirror versus oscillating mirror**: With a rotating polygon mirror, the scan rate is the number of scan lines per second (Figure 2a). For example, a 100 Hz scan rate means that the scanner can provide 100 parallel scan lines every second. With an oscillating mirror, a scan frequency of 100 Hz means that the mirror completes 100 *full oscillating cycles*, each cycle consisting of *two* scan lines (Figure 2b). In other words, an oscillating mirror at 100 Hz scan frequency generates 200 scan lines on the ground. Not knowing this quantitative difference when comparing distinct scanners with the “same” scan frequency may lead to misinterpretation of system capabilities and miscalculation of point spacing for a survey mission.

**Scan field of view (FOV) versus scan rate (or scan frequency)**: In the case of an oscillating mirror, two parameters—maximum scan rate and maximum scan angle—are not only interrelated but also inversely proportional to each other. Their product determines the *maximum scanner velocity* that a particular scanner can practically achieve, characterized by the maximum scan product (SP). The maximum SP represents the real physical limitation of an oscillating mirror scanner and, in combination with the scan pattern driving signal, determines the maximum load allowed for the scanner. Since the maximum SP characterizes the maximum achievable scanner velocity and simultaneously accounts for both the highest scan rate *and* the maximum scan FOV, it also determines the maximum possible area coverage rate for a lidar system.

It was shown (Ussyshkin *et al.*, 2008b) that the maximum scan rate (or frequency) available for a particular lidar system may have limited practical advantage if the maximum scan angle available at this scan rate reduces the scanner FOV to impractical limits. On the other hand, given an equivalent scan pattern, a higher SP indicates a wider scan FOV available for the maximum scan rate and consequently a scanner that can operate at a higher scanner velocity to complete the job faster. However, lidar system users should remember that SP values calculated for different types of scan patterns are derived dissimilarly and should never be compared directly as counterparts.

In summary, for any type of oscillating mirror, regardless of scan driving signal differences, the maximum scan rate (that is, frequency) is always linked to the maximum scan angle available for this frequency. That is why the seeming advantage of large numbers on the specification sheet may not equate to any actual benefit, and users should always examine the numbers by considering real operational scenarios and practical limitations.

## 3. ACHIEVABLE ACCURACY VERSUS ACCURACY SPECIFICATIONS

Of particular importance are numbers on a specification sheet characterizing lidar data accuracy. These numbers represent one of the most important system specifications. However, these numbers can be very misleading, if the context of the reference conditions and deriving methodologies are not taken into account. While instrument accuracy specifications are provided by the manufacturers, translating the specification numbers to real-world achievable accuracy is a challenge usually left to the end user, and it has long been a subject of different interpretations (Ussyshkin *et al.*, 2006a). Moreover, without widely accepted guidelines for deriving accuracy numbers, lidar system manufacturers typically use different methodologies for accuracy specifications.

Owing to the nature of lidar data collection, many factors affect the real-world accuracy of lidar data, including extreme operational parameters (such as a very wide scan FOV and very high flying altitudes), strong variations in the target physical properties (such as size, slope, and reflectivity), and so forth. While some of these factors may be defined and described on a specification sheet, not all of them can be accounted for even in the most detailed document, and that is why the impact of some of these factors on data accuracy is sometimes either ignored or underestimated. However, it is very important for the user to estimate the influence of these factors on achievable data accuracy. We will give several examples showing the relationships between unexpected or underestimated factors and their impact on lidar data accuracy.

### 3.1 Dynamic Range of Intensities and Data Accuracy

Though usually interpreted as essential to intensity data and image quality, the dynamic range of intensity that a lidar system can accommodate (also known as the “intensity digitization specification”) may be extremely important for the achievable range data accuracy in surveys where strong variations in the returned signal are expected due to the highly variable reflective properties of the terrain and/or the size and shape of the objects on the ground (Ussyshkin *et al.*, 2007). Examples of such surveys are corridor projects over highways covered by dark asphalt with white painting on top, or power transmission line corridors where the signal strength from thin wires is very weak compared to that from the ground. In these cases, if the receiver’s dynamic range is limited and cannot accommodate a wide range of signals, weak signals could be lost, or strong signals could saturate the receiver, consequently compromising range data accuracy (

Figure 4). Range data accuracy may even worsen when small-size surveyed targets are suspended over terrains with highly variable reflective properties (black/white roads or snow/wetland).

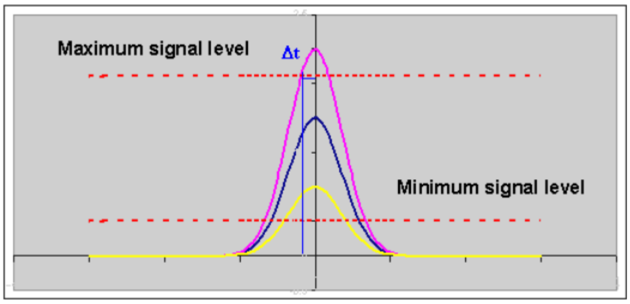

Figure 4. Simplified illustration of a possible error due to limited dynamic range of the lidar receiver: If the signal variations exceed the receiver’s signal dynamic range, range measurement accuracy may be compromised.

On the other hand, lidar system manufacturers typically characterize lidar performance for the most general case of targets: that is, flat open terrain with uniform reflective and physical properties and no strong signal variations within a single mission. Thus, the accuracy numbers presented on a system specification sheet may be inapplicable to many real-life operating scenarios in which strong signal variations occurring on a microsecond time scale may challenge the lidar receiver’s dynamic range.

Hence, besides range accuracy, the lidar system user should also account for possible data voids because of a limited dynamic range of intensities of a particular lidar system. The lidar user may have to check the data dropout rate during data collection to avoid unacceptable data voids. If the lidar system's dynamic range is insufficient to handle strong signal variations resulting from the highly variable reflective properties of the targets, additional passes may be required to cover areas with problematic targets.

### 3.2 Laser Footprint Size and Data Accuracy

Laser footprint size is an additional factor that should be clearly understood regarding lidar accuracy. One cannot directly specify the accuracy of a lidar system without taking into account the finite size of the laser footprint. Under actual survey conditions, there is always uncertainty in where a laser spot of finite size hits the target. For example, in the case of a building edge, uncertainty in the horizontal position is determined by the laser footprint size, which is typically about 25 cm for a 1-km flying height. This factor only brings the horizontal accuracy of the building edge down to the 1/4000 level regardless of other lidar subsystem performance characteristics such as the scanner, rangefinder, and GPS/INS system.

Mathematical modelling (Ussyshkin, 2007b) of the vertical and horizontal positional errors due to the finite size of the laser footprint on the ground shows that this consideration becomes critical for the accuracy of targets producing partial signal return, tilted targets, or sloped terrain. Figure 5 shows some results of this modelling where the elevation error $\Delta z$ and cross-track component $\Delta y$ of the horizontal error are calculated as a function of the scan angle and the slope of the terrain. These results show that to maintain reasonable data accuracy for data collected over sloped and highly non-uniform terrains, the user should reduce scan angles and flying height and plan a project accordingly.

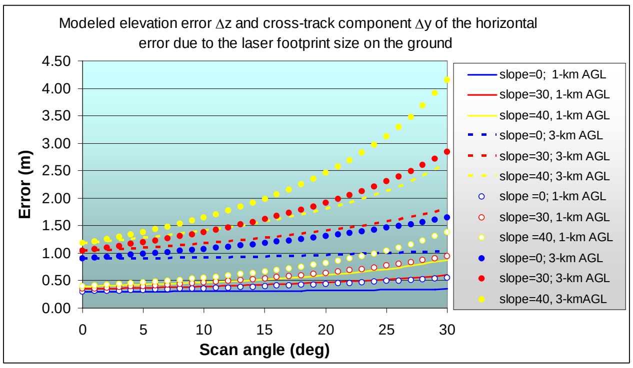

Figure 5. Modelled vertical and horizontal positional errors caused by the finite size of the laser footprint on the ground, if the beam divergence is 0.3 mrad (full angle). Solid and dashed lines represent elevation error $\Delta z$; solid and empty circles represent $\Delta y$ (cross-track) component of the horizontal error.

### 3.3 FOV and Data Accuracy

The analysis of the impact of the laser footprint size on data accuracy presented above shows that both vertical and horizontal accuracy strongly depend on the scan FOV (or scan angle). In fact, as the scanner FOV (or maximum scan angle) widens, the expected deterioration of data accuracy around the scan edges generally becomes more significant. Additionally, errors in the position and orientation system (POS) data also contribute to the deterioration of data accuracy at large scan angles (Ussyshkin *et al.*, 2008a).

As the lidar user might be aware, some manufacturers explicitly specify the lidar's scan FOV while others may not. In either case, a question about the accuracy numbers given on the specification sheet remains open: Does the specification sheet indicate scan nadir accuracy (the best), scan edge accuracy (the worst), or something in between? Over-emphasizing accuracy numbers without indicating the scan angle can lead to a misinterpretation of system capabilities and wrong expectations on data quality for the entire project area. The horizontal accuracy analysis presented below helps to quantify the impact of scan FOV on expected data accuracy.

### 3.4 GPS/INS System and Data Accuracy

GPS/INS data quality is often considered a limiting factor in achieving the best accuracy of lidar data (Ussyshkin *et al.*, 2006b). To quantify the impact of GPS and INS data quality on the accuracy of a lidar system, we have launched a study on the attainable horizontal accuracy of an airborne lidar system. The results of this study have been presented recently (Ussyshkin *et al.*, 2008a; Ussyshkin *et al.*, 2008b). Figure 6represents some results of that study, which were based on theoretical modelling of the best achievable horizontal accuracy. While error due to laser footprint size was not taken into account in the study, the rangefinder and scanner error were limited to 5 cm and 0.001° respectively, and GPS/INS errors were modelled based on Applanix's performance specifications for POS AV-510 and 610 models (Mostafa *et al.*, 2001).

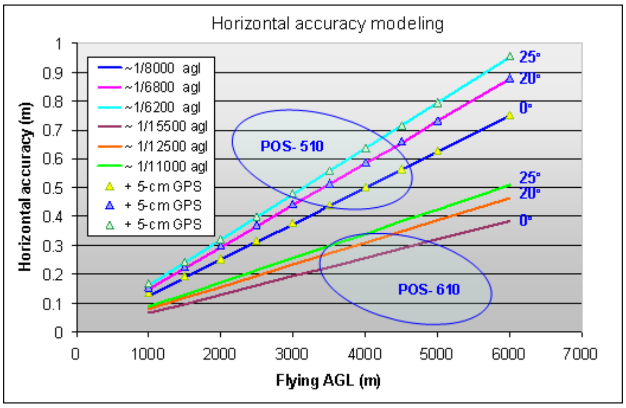

Figure 6. Theoretically achievable horizontal accuracy in an airborne lidar system equipped either with POS AV-510 or POS AV-610 (or equivalents). All solid lines represent modelling results with zero GPS error; dotted lines represent results with 5-cm GPS error.

The results of the theoretical analysis of positional errors partially represented in Figure 5 and Figure 6 show that the combined impact of laser footprint size and GPS/INS system on lidar data accuracy may make data collected at very high altitudes and very wide scan angles not usable for most practical applications. Further details of this study, including comparison of theory versus practice, are found in our previous publications (Ussyshkin *et al.*, 2008a; Ussyshkin *et al.*, 2008b).

Based on the results of this study, we have concluded that POS (or any GPS/INS system) data accuracy has the most dominant impact on the attainable horizontal accuracy of airborne lidar data. Hence, the specified horizontal accuracy numbers of two airborne lidar systems equipped with the same or equivalent GPS/INS systems must be identical, if these numbers are derived by similar methodologies, and if the same or similar reference set of operating conditions has been considered.

### 3.5 Post-Processing and Data Accuracy

Another factor that may have a crucial impact on the accuracy numbers on the lidar system specification sheet is the data processing procedure. Even after thorough consideration including a reference set of operating parameters, a reference target, and a reference set of data collection conditions, the data processing procedure and the various processing algorithms applied to the raw lidar data may introduce or reduce errors. The data set might be further adjusted, optimized, or smoothed by using third-party software. Moreover, additional data optimization algorithms could also be applied to data already processed and calibrated by the manufacturer's proprietary software. After a series of data processing procedures, the *final* accuracy numbers may look very different as a result. Since every commercial lidar system manufacturer uses a unique set of proprietary procedures to determine data accuracy, there is always a "grey" area around the accuracy numbers on the lidar system specification sheet.

Based on the results of a recent study on the impact of the data processing procedure on lidar accuracy numbers (Pokorny *et al.*, 2008), we have concluded that the optimization algorithms applied to the processed lidar data may significantly improve the derived accuracy numbers. Table 1 and Table 2 show some results of this study, in which two different software tools and two different algorithms were used to calculate the RMSE (root mean square error) and standard deviation for the vertical accuracy of data collected by three different ALTM systems at slightly varied flying altitudes of about 1 km and under similar operational conditions.

| | **Software tool 1** | | **Software tool 2** | |
|---|---|---|---|---|
| | **Algorithm 1** | **Algorithm 2** | **Algorithm 1** | **Algorithm 2** |
| System 1 | 0.096 | 0.095 | 0.087 | 0.086 |
| System 2 | 0.053 | 0.047 | 0.054 | 0.047 |
| System 3 | 0.074 | 0.054 | 0.074 | 0.054 |

Table 1. Comparison of z-RMSE values for the lidar data processed by different software tools and different algorithms

| | **Software tool 1** | | **Software tool 2** | |
|---|---|---|---|---|
| | **Algorithm 1** | **Algorithm 2** | **Algorithm 1** | **Algorithm 2** |
| System 1 | 0.062 | 0.052 | 0.061 | 0.051 |
| System 2 | 0.043 | 0.036 | 0.044 | 0.035 |
| System 3 | 0.072 | 0.057 | 0.072 | 0.057 |

Table 2. Comparison of standard deviation values for the lidar data processed by different software tools and different algorithms

The comparisons in Table 1 and Table 2 show clearly that the final accuracy numbers presented on the lidar system specification sheet may be improved by 10-30% simply by using different processing algorithms, either developed internally by the lidar system manufacturer or provided by third-party software.

In addition, since overall lidar data accuracy strongly depends on the accuracy of the position and orientation data, post-processing software tools available in advanced GPS/INS systems may also have a significant impact on final data accuracy. A prime example is the new POSPac 5.0 processing package offered by Applanix/Trimble, which has proved to be even more robust than the POSPac 4.4 currently used with ALTM/Gemini and is capable of handling steeper banking angles without compromising the specified accuracy (Hutton *et al.*, 2007). In tests performed at Optech (Boba *et al.*, 2008), processing with the POSPac 5.0 has consistently shown improved POS data accuracy that, in turn, improved the overall accuracy of ALTM/Gemini data.

Thus, the data accuracy derived immediately after data processing may look noticeably different from the numbers derived after applying additional processing tools to optimize the data. Moreover, the methodology that the data processing workflow uses to derive the accuracy numbers may vary from one manufacturer to another. Therefore, the final accuracy numbers derived by different methodologies would not be obviously valid for sensible comparison.

## 4. CONCLUSION

To bridge the gap between the numbers on a lidar specification sheet and expected system performance in the field, the lidar system user must understand the underlying premises and relationships between these numbers and plan an airborne survey project accordingly.

It was shown that in addition to laser PRF, which determines data collection efficiency, the scan pattern and beam deflection mechanism used in a particular lidar system may influence ground point density and area coverage rate and consequently affect the operating parameters for a planned mission. The dynamic range of intensities that a particular lidar system can accommodate may also significantly enhance or reduce achievable data quality and accuracy. Hence, to collect accurate data without voids over highly variable terrain, the user should carefully evaluate a lidar system's dynamic range capabilities and limitations.

In addition, it was shown that the combined impact of laser footprint size and the GPS/INS system on lidar data accuracy can make the data collected at very high altitudes and very wide scan angles not usable for most practical applications. Also, the analysis of the impact of processing algorithms and third-party software tools on data accuracy indicated that accuracy numbers derived by different processing workflows may look noticeably different. Thus, without consensus in the industry on how to derive the lidar data accuracy numbers, lidar users should remember that the numbers they see on lidar specification sheets across different manufacturers may not be valid for comparison and may not be applicable to certain survey conditions.

In conclusion, knowing the relationships underlying manufacturer-derived lidar specifications and the many factors that can alter actual data collection efficiency and quality will help the user to develop more realistic expectations of system capabilities and match these capabilities more closely to project requirements.

## ACKNOWLEDGEMENTS

The authors are very grateful to Martin Pokorny for his contribution to this paper.

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