PERFORMANCE ANALYSIS OF ALTM 3100EA:
INSTRUMENT SPECIFICATIONS AND ACCURACY OF LIDAR DATA

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KEY WORDS: LiDAR, laser scanning, DEM/DTM, accuracy, performance

ABSTRACT:

Over the last decade the number of airborne lidar systems currently deployed and operating in the field has grown impressively. This growth has intensified the level of competition among lidar equipment manufacturers. As manufacturers vie for increased market share with claims of ever higher accuracy specifications, lidar end users wonder how these specifications actually affect achievable accuracy of the lidar data.

Aware of the interest that professional organizations such as ISPRS/ASPRS have shown in establishing quality control guidelines for reporting accuracy in lidar data, Optech Incorporated, a leading manufacturer of airborne lidar equipment, conducted a series of studies that examined issues that included, among others, vertical accuracy and Position and Orientation System (POS) performance. Since accuracy specifications can be the product of different testing methodologies and subject to the interpretation of data, the final arbiter of competing claims is actual system performance. The studies that Optech carried out included performance analyses of the ALTM 3100EA laser mapping system. This instrument demonstrated that it is capable of producing mapping data with relative accuracies on the sub-decimeter level. However, the limiting factors in obtaining overall absolute sub-decimeter accuracies are often due to the performance of various subsystems that contribute to the total ALTM error budget. This paper represents the manufacturer's effort to relate the engineering analysis of instrument performance to what is demonstrably achievable accuracy in the lidar data of end users.

1. INTRODUCTION

1.1 Overview

Airborne laser scanning technology has emerged as the preferred operational tool in remote sensing, surveying and mapping. It is capable of generating high-density, high-accuracy digital elevation data for end users in a wide range of applications in both the commercial mapping industry and academic research. The combined advantages of fast field operation, comparatively low cost and impressive reduction in post-processing time have enabled the rapid development of commercial lidar surveying. Over the last decade, the number of airborne lidar systems currently deployed and operating in the field has grown impressively (Renslow, 2005). This growth has intensified the competition among lidar equipment manufacturers, who claim ever-improving performance specifications. On the other hand, such intensive marketing dynamics are strongly motivated by the increased awareness of the unique advantages of this technology, and the growing demands for highly accurate digital elevation data by lidar data end users (Flood, 2001a).

1.2 Motivation

As the lidar instrument manufacturers compete for increased market share with claims of higher performance specifications, there is growing concern in the community of lidar data providers and end users regarding the achievable accuracy of the airborne lidar data. Although recent advances in airborne lidar technology have resulted in the dramatic improvement of lidar data quality (i.e., higher density of points and better accuracy), there are certain misunderstandings about how the lidar instrument's operational capabilities influence the achievable accuracy of the lidar data. Furthermore, the link between the final accuracy of the lidar data and the existing accuracy standards developed for mapping and other more mature technologies is not very well understood (Flood, 2001b). The lack of industry-wide definitions and standards for the characterization of the lidar instrument performance and the quality of the end product may lead to confusion and skepticism throughout the lidar community.

1.3 Aims

Considering the interest of professional organizations such as ISPRS and ASPRS in establishing quality control guidelines for reporting accuracy of lidar data, and also addressing the growing concerns among the user community, Optech Incorporated, a leading manufacturer of airborne lidar equipment, conducted a series of studies that examined the actual accuracy of the lidar data collected by the ALTM 3100 system.

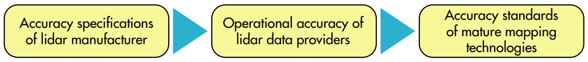

Figure 1: Accuracy interpretation levels

This paper presents an overview of the studies performed by Optech in the context of the overall error budget of the lidar system. It will also discuss the importance of the correct understanding of the lidar system specifications provided by the manufacturer and will explore the links from the instrument specifications to the operational accuracy of the lidar and the accuracy standards expected by the end users (Figure 1).

2. UNDERSTANDING LIDAR SPECIFICATIONS

2.1 Specification Terminology Variations

Although the basic principles of airborne laser altimetry are well known, there are significant variations in design of commercially available instruments. Due to the lack of clearly established guidelines for the characterization of the operational capabilities and performance of commercial lidar systems, some technical specifications and parameters may vary among manufacturers. For example, the laser beam divergence that determines the spot size on the ground can be specified in terms of 1/e or 1/e^2, full-angle or half-angle; the laser footprint diameter on the ground could also be expressed in terms of 1/e or 1/e^2. The maximum detectable range might be characterized by operational altitude (above ground level, AGL), or maximum slant range for the maximum slant angle, which would look much more impressive than AGL specifications. Table 1 gives some examples of the technical airborne lidar specifications using different terminology to characterize the same or similar operational or performance parameters.

Table 1: Interchangeable specification terminology

<table>
<tr><th>Characteristic</th><th colspan="4">Terminology</th></tr>
<tr><td>Laser Pulse Frequency</td><td colspan="2">Pulse repetition rate</td><td colspan="2">Data collection rate</td></tr>
<tr><td>Laser Beam Divergence</td><td>1/e</td><td>1/e^2</td><td>Full angle</td><td>Half angle</td></tr>
<tr><td>Footprint Size on the Ground from Reference Altitude</td><td colspan="2">Footprint diameter, 1/e</td><td colspan="2">Ground spot diameter, 1/e^2</td></tr>
<tr><td>Maximum Scan Angle</td><td colspan="2">±Half-angle</td><td colspan="2">Full-angle/full FOV</td></tr>
<tr><td>Scanning Rate</td><td colspan="2">Scan rate</td><td colspan="2">Scan frequency</td></tr>
<tr><td>Survey Altitude</td><td colspan="2">Operational altitude</td><td colspan="2">Slant range for max. scan angle</td></tr>
<tr><td>Vertical Accuracy</td><td colspan="2">Vertical (elevation) accuracy for the max. scan angle</td><td colspan="2">Vertical (elevation) accuracy versus scan angle</td></tr>
<tr><td>Horizontal (Planimetric) Accuracy</td><td colspan="2">Horizontal accuracy for the max scan angle</td><td colspan="2">Planimetric accuracy versus scan angle</td></tr>
</table>

These examples show that picking up a number from a specification sheet of the instrument may lead to misinterpretation of the instrument's operational capabilities as well as of the achievable accuracy. Since the data accuracy typically depends on the scan angle, for instance, the accuracy specified for the maximum scan angle appears much more conservative when compared to accuracy specified as a function of the scan angle. Careful analysis of the instrument specification sheet is essential for correct understanding of the system parameters.

2.2 Is PRF the primary figure of merit?

The quality of the end product (i.e., the accuracy of the lidar data) is one of the most important system characteristics determining the system selection for a particular application. However, for a commercial lidar system, other performance specifications could be as important as the data accuracy—how fast the survey could be completed, what density of points could be provided, etc. When cost effectiveness of the survey time is considered, the achievable point density on the ground per unit time becomes the parameter of primary importance. Although it is a function of the entire set of the operational parameters including the pulse repetition frequency (PRF), scan frequency, scan angle, altitude, platform speed, etc., the PRF is considered to be the major parameter determining the cost effectively of the survey. As a result, pulse repetition rate has become a prime differentiating factor in the marketing of both sensors and data collection services (Flood, 2001a).

However, judging a lidar system on a single parameter can lead to misinterpretation of the instrument's capabilities. Taking into account the other system characteristics, a detailed analysis of the specifications may lead to surprising results. As an example, consider the laser repetition rate. In general, a higher laser repetition rate provides greater area coverage and/or denser spot spacing. In terms of determining area coverage and spot spacing, the single figure of laser repetition rate is not sufficient. One has to look at how the laser points are distributed, not just how many there are. Table 2 shows a simple breakdown of the distribution of the laser points for a scan swath of ±20° for saw-tooth and sinusoidal scan patterns (Figure 2).

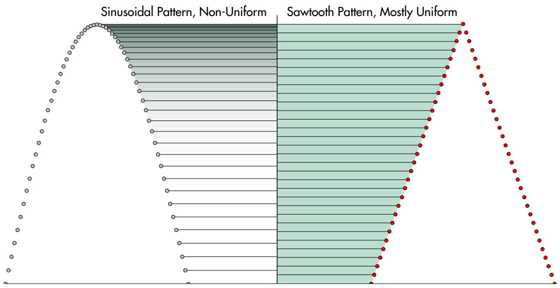

Figure 2: Sinusoidal vs. saw-tooth scan patterns

Considering the central ±10° of the swath for these two patterns, it shows that the saw-tooth pattern may provide higher density of points, just by keeping the uniform point distribution across the major part of the swath. As for the sinusoidal scan (which has its own advantages), the density of points is minimal at the center of the swath and grows towards the ends of the scan line. The key distinction here is that the saw-tooth scan provides a constant speed for most of the swath, while the sinusoid scan moves fastest in the center of the swath and slows at the edges. This effectively concentrates the laser points at the edges of the swath for sinusoidal scans.

Table 2: Laser point distribution comparison

Swath Portion	Saw-Tooth	Sinusoidal
0°–5°	23%	15%
5°–10°	23%	17%
10°–15°	23%	21%
15°–20°	30%	47%

Table 3 continues this specification comparison by examining the data collection rate and the point distribution pattern of two systems. The system operating at 100 kHz and using the saw-tooth scan pattern deposits 46,000 laser shots per second within ±10° of the swath (46% x 100,000), but the system operating at 150 kHz and using the sinusoidal pattern deposits 48,000 laser shots per second (32% x 150,000). Thus, if both systems operate at the same altitude and scan frequency, they would effectively provide almost the same point spacing for the central half of the swath, even though one operates at 100 kHz, and the other at 150 kHz.

Table 3: Ground point spacing comparison for central 10° swath portion

Specification	Saw-Tooth Scan	Sinusoidal Scan
Percentage of Total Shots	46%	32%
Laser PRF	100 kHz	150 kHz
Data Collection Rate	46,000 shots per second	48,000 shots per second
Ground Point Distribution Across Swath	Mostly uniform	Lowest density at nadir, highest density at max. scan angle

An additional key survey limitation at higher laser repetition rates is the operational altitude. Lidar systems operate on a time of flight principle—the range to the ground is determined by measuring the time that the pulse leaves the lidar transmitter and the time that the ground reflection is received. This assumes that the current pulse has completed its round trip to the ground and back before the next pulse is emitted. At very high laser repetition rates, this forces the aircraft to fly lower. For example at a pulse repetition rate of 100 kHz, the time between laser pulse firings is only 10 µs. The previous pulse must complete its trip to the ground and back in a time shorter than 10 µs. This limits the aircraft altitude above ground to less than 1.5 km. Thus having a high laser repetition rate does not translate directly into greater area coverage because, at the higher laser repetition rate, the aircraft is forced to fly lower, reducing the swath width and the area coverage rate.

Other consequences of higher repetition rates may include reduced elevation accuracy, and loss of sensitivity to dark surfaces. Such consequences are also not addressed by looking at the single parameter such as laser repetition rate.

The type of analysis presented in Table 2 and Table 3 clearly indicates that the pulse repetition rate alone may not represent the highest achievable density of ground points and data collection rate. In addition, it may compromise the accuracy of the lidar data. Since an airborne scanning lidar is a complex system, none of the technical specifications should become a single representative of the system's operational capabilities. Furthermore, until a well defined set of parameters characterizing the mapping lidar system operational capabilities and performance is widely accepted as a standard, a careful analysis of the performance specification sheet of any lidar system is recommended.

3. THE SYSTEM ERROR BUDGET

3.1 Ground Point Accuracy

Ground point accuracy is the key performance specification claimed by lidar system manufacturers and lidar data providers, but it has always been the subject of different interpretations among the end users of lidar data. Because there are no clearly defined sets of operational conditions that might affect the lidar data accuracy, the instrument manufactures may claim the best case or averaged performance specifications, or specify very conservative values.

In order to estimate possible, or even expected, variations in the achievable data accuracy, the entire error budget of the lidar system should be considered. Due to the complexity of lidar systems, the accuracy of the measured data is determined by the error contribution from the core subsystems: the laser rangefinder, the scanner, and the GPS/IMU navigation sensors. Recently, the GPS and IMU sensors have become commercially available as an integrated direct geo-referencing Position and Orientation System (POS) that provides GPS position measurements integrated with an IMU orientation solution (Applanix, 2006a). The overall error budget of an airborne lidar system can be described as shown in Figure 3.

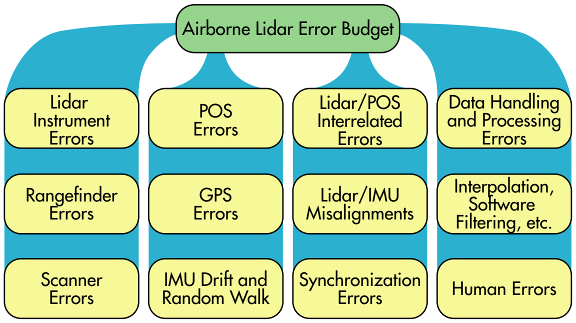

Figure 3: Error budget for airborne lidar systems

Thorough analysis of the contribution from all sources of errors is required for the optimal design of an integrated instrument. Well-balanced performance of the subsystems could minimize the overall error budget and improve the final accuracy of the lidar data. A classical overview of the error sources of an airborne lidar and interrelations between the instrument specifications and overall system accuracy was presented by Baltsavias in the paper titled "Airborne Laser Scanning: Basic Relations and Formulas" (Baltsavias, 1999).

3.2 Elevation and Planimetric Error

Most manufacturers and service providers specify instrument accuracy in terms of vertical (elevation) and horizontal (planimetric) accuracy. Each of the error sources shown in the error budget (Figure 3) affect both elevation and planimetric accuracy, but some could be characterized by a dominant contribution to a single type of error. The time-of-flight range measurement error would mainly contribute to the elevation error while the system operates with relatively narrow swath over flat terrain. The angular pointing error caused by the contribution from the scanner subsystem would mainly affect the planimetric error at small scan angles, but it might also lead to significant elevation errors at large scan angles. The GPS-determined position error might cause a large elevation bias, which could be removed by using reference ground control data. The random noise and uncompensated gyro drift in the IMU system would lead to the errors in orientation angles (i.e., roll, pitch and heading), which would primarily propagate to the planimetric coordinate error. For a typical commercial airborne lidar system, the vertical accuracy of the lidar data is significantly better than the planimetric accuracy (Vosselman, 2001).

3.3 Absolute versus Relative Accuracy

Both vertical and horizontal accuracy may be affected by significant systematic errors, which typically dominate over random errors (Maas, 2003). Misalignments between the sensor body frame and the POS system can be minimized by a rigorous system calibration procedure, but are not easily eliminated. The residual calibration errors and the synchronization error can cause shifts and tilts of the data strips. There are several techniques to remove the residual biases from the lidar data (Burman, 2002; Toth, 2005). Still, raw absolute accuracy of the lidar data is mostly determined by the POS system (i.e., GPS-related bias) and is still significantly worse than the relative accuracy, determined by the lidar instrument itself, which is often capable of producing range accuracy at sub-decimeter level (Ussyshkin, 2006).

4. THE ALTM 3100 EA

4.1 Product History

Optech's ALTM 3100 system was introduced to the market a few years ago with improved specifications compared to earlier ALTM models. The vertical accuracy, specified as 15 cm, 1-σ for 1 km operational altitude has been widely used by data service providers and throughout the lidar community. The horizontal accuracy (being inversely proportional to the flight altitude) was specified as 1/2000 from the flying height, which translates to 50 cm planimetric accuracy for 1 km of flight altitude.

As a major competitor in the rapidly developing airborne laser scanning industry, the ALTM 3100 system has been evolving over the years. Despite such rapid change and added features, the specified accuracy of the ALTM 3100 has not been changed since its debut. The question of whether the system accuracy has indeed remained constant is crucial. To answer this question, Optech carried out studies on the performance of the advanced model of the system. A recent series of studies on the vertical accuracy of ALTM 3100 system demonstrated that this instrument is capable of relative accuracies on the sub-decimeter level (Lane, 2005). Figure 4 presents some results of this study, where the performance of several recent ALTM systems was analysed. The study results illustrate that the newly built systems consistently collected data that was well above the accuracy specifications quoted several years ago. The study has also shown that Optech could potentially change the accuracy quote from 1-σ to 2-σ specifications. In essence, this analysis showed that the advanced ALTM 3100 is capable of relative accuracies on the sub-decimeter level, and that the accuracy specifications quoted several years ago are too conservative to characterize its current performance.

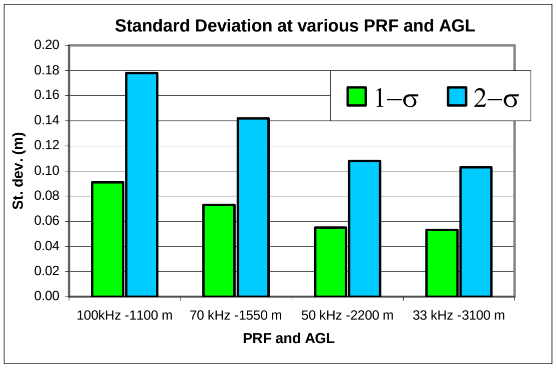

Figure 4: Standard deviation in elevation data demonstrated by the ALTM 3100

A new ALTM 3100EA (Enhanced Accuracy) model was recently announced. The new model still offers all the functionality and performance of the previous ALTM 3100 systems, but now enables users to achieve even greater accuracies for demanding large-scale mapping requirements. Under optimal conditions, the system is capable of achieving the elevation accuracies as high as ±3 cm, 2-σ at 500 m elevation, 33 kHz PRF with ±10° scan angles. Optech's ALTM 3100EA provides data acquisition rates of up to 100,000 points per second with full waveform digitization, and digital camera options. Some of the performance specifications of ALTM 3100EA are presented in Table 4.

Table 4: Selected performance specifications for the ALTM 3100 EA

Parameter	Value *(quoted accuracies do not include GPS errors)*				
Operating Altitude	80–3500 m nominal				
Laser PRF	PRF (kHz)	33	50	70	100
	Max. AGL (km)	3.5	2.5	1.7	1.1
Planimetric Accuracy (1–σ)	1/5500 x altitude				
Elevation Accuracy (1–σ)	PRF (kHz)	500 m AGL	1000 m AGL	2000 m AGL	3000 m AGL
	33	<5 cm	<10 cm	<15 cm	<20 cm
	50				N/A
	70	<10cm			N/A
	100			N/A	N/A
Ground Spot Distribution	Uniform for 96% of swath; saw-tooth pattern				
Beam Divergence	Dual: 0.3 mrad (1/e) or 0.8 mrad (1/e), full-angle				
Scan Frequency	Variable; maximum 70 Hz				
Scan Angle	Variable from 0 to ±25°, in increments of ±1°				
Scan Product	Scan angle × scan frequency ≤ 1000				

Table 5 and Table 6 illustrate the excellent overall horizontal and vertical accuracy of ALTM 3100EA achieved during calibration flights. Note that the swath here is ±25°; the achievable accuracy would be even better for a reduced swath.

Table 5: Horizontal accuracy results for ALTM 3100EA two calibration flights

Flight Altitude (m, AGL)	Laser Freq. (kHz)	FOV (±deg)	Attribute	Achieved Accuracy (m, 1-σ)	EA spec. (m, 1-σ)
1200	70	25	X	±0.111	±0.22
			Y	±0.193	
1200	70	25	X	±0.135	±0.22
			Y	±0.115	

Table 6: Elevation accuracy results for ALTM 3100 EA over several calibration flights

Flight Altitude (m, AGL)	Laser Freq. (kHz)	FOV (±deg)	Achieved Accuracy (m, 1-σ)	EA spec. (m, 1-σ)
1100	100	25	±0.129	± 0.15
1700	70	25	±0.141	± 0.15
2500	50	25	±0.166	± 0.20
3500	33	25	±0.194	± 0.20
1100	100	25	±0.133	± 0.15
1700	70	25	±0.062	± 0.15
2500	50	25	±0.173	± 0.20
3500	33	25	±0.060	± 0.20

It is important to keep in mind that these accuracy specifications do not include the GPS bias error. The quoted accuracies could be achieved only by applying a block adjustment to the entire data set that coincides with the assessed vertical error produced by systematic GPS errors. Furthermore, the ALTM must receive GPS data of sufficient quality under specific operational conditions (Optech, 2006). Generally, the accuracy quoted by the system manufacturer is affected by errors caused by physical or environmental conditions in the field (e.g., distance from base station or type of terrain). Although some of these errors can be minimized with proper planning before the flight, some are unavoidable. This is exactly the point where the quoted instrument performance specifications and the operational accuracy of the collected data may diverge.

5. INSTRUMENT ACCURACY SPECIFICATIONS VERSUS FINAL DATA ACCURACY

Due to the nature of lidar data collection, various operational considerations, including variations in geo-positioning data quality, the ground conditions, and the weather conditions, will significantly affect the achievable point accuracy in the field. Several factors make the achievable, operational accuracy of the lidar data worse than the theoretical one. For example, the final accuracy may depend more on the shape of the ground and surface cover than on the accuracy specifications of the lidar system itself (Hodgson, 2006). The density of the canopy cover may also affect accuracy of the ground DTM (Turton, 2000). Furthermore, additional errors might be introduced during data post-processing to affect the accuracy of the lidar-derived end products; and finally, the accuracy of the DEM derived from the lidar points may include various errors due to data interpolation and classification (Smith, 2005).

Several empirical studies have been performed to determine the overall accuracy that can be achieved with lidar and to assess achievable accuracy for various mapping applications (Adams, 2002, Bowen 2002, Hodgson 2003 and references therein). However, the misinterpretation of the instrument accuracy specifications with the achievable accuracy of the lidar data is still common. Figure 5 shows a schematic breakdown of the factors that are often not taken into account when the final accuracy of lidar data is considered. These factors may, and usually do, introduce additional errors that will greatly affect the quality of the lidar data. These factors may be divided into three subcategories: factors related to the operation and calibration of the lidar instrument; environmental and flight operational conditions; and additional errors that may arise during data post-processing.

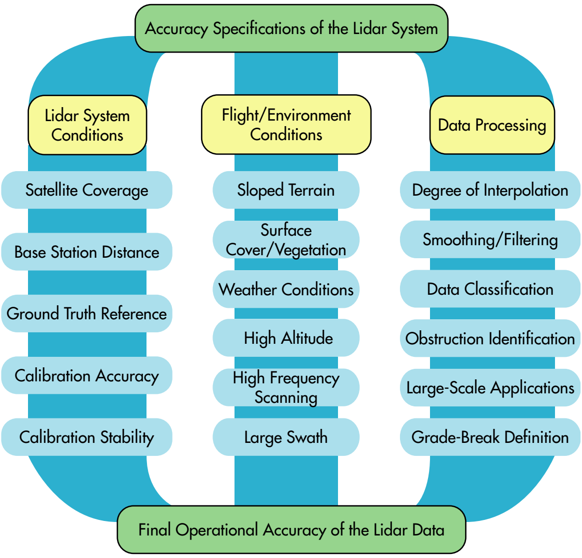

Figure 5: Final accuracy of the lidar data

Lidar Instrument Conditions

- Quality of GPS signal, such as the number and elevation of satellites, distance to the base station, and electromagnetic interference with the GPS signal.
- GPS/INS performance compliant with the quoted performance specifications: achievable post-processed accuracy may be worse than the specified one, if the ground-truth reference data are not taken into account (Applanix, 2006b)
- System calibration: accuracy and stability of the calibration parameters from flight-to-flight versus different set of operational parameters, temperature, vibrations, etc.

Flight/Environment Conditions

- Slope terrain
- Surface coverage/ dense vegetation
- Environmental conditions such as wind, reduced visibility, and wet surfaces.
- Survey requiring wide swath, high scan frequency and high altitude data collection
- Aided eye-safety requirements

Data Handling/ Processing/Application

- Degree of interpolation: DEM/DTM grid spacing versus density of the lidar point
- Smoothing/filtering algorithm
- Data structuring and segmentation
- Data classification
- Obstruction identification
- Large-scale applications
- Grade-break definition, etc.

Thus the fact that the final accuracy of the lidar data and post-processed data, may look worse than the quoted accuracy of the instrument should not be considered as a system's failure to meet the performance specifications. The manufacturer, in defining an accuracy specification, has to define a particular measurement scenario. This is typically a well-defined surface where the results will be repeatable. In the real world, however, surfaces are sloped and changing. Vegetation cover affects the range measurements and GPS quality is variable.

6. EVOLVING GUIDELINES AND STANDARDS

Topographic lidar systems produce surface elevation in XYZ coordinate data points, and there are many end products that can be derived from raw point data. Most lidar data providers can derive the following products:

- Digital elevation models (DEMs)
- Digital terrain models (DTMs)
- Bare-earth elevation data
- Triangulated irregular networks (TINs)
- Breakline definition
- Terrain contour maps/plans
- Shaded relief
- Slope and aspect
- Ground profiles.

From the information presented above, it is clear that the accuracy specifications of a lidar-derived product may not be the same as the claimed accuracy of the lidar instrument itself. On the other hand, many lidar data users seek compliance between the accuracy of lidar-derived products and the existing standards developed for older, more mature technologies like traditional photogrammetric mapping. It is important to keep in mind that the nature and the structure of the error budget of lidar and photogrammetric systems are very different. Photogrammetry has the great advantage of excellent planimetric accuracy, while providing relatively poor elevation accuracy. By contrast, a typical lidar mapping system has larger planimetric error and smaller elevation error. Therefore the accuracy standards developed for traditional mapping based on photogrammetric data are not fully applicable to lidar-derived mapping products.

The ASPRS committee recommends all mapping professional adhere to and follow the new guidelines, "Vertical Accuracy Reporting for Lidar Data", while generating mapping products derived from lidar data (ASPRS Lidar Committee, 2004). A series of project studies conducted by Airborne 1 Corporation gives an excellent example of the thorough analysis of the lidar-derived DEM accuracy against the existing mapping standards developed by NMAS, ASPRS and NSSDA (Airborne 1 Corp., 2004). According to this analysis, both vertical and horizontal accuracy of the DEM derived from ALTM data met or exceeded most of the applicable standards with a high level of confidence. Hence, the provider can certify the lidar product to those particular standards.

As airborne terrain lidar mapping technology is becoming widely adopted for various applications, relevant government agencies and professional associations such as ASPRS, NOAA, FEMA, NSSDA and others are working in coordination to develop broad standards for lidar-derived products that can be applicable as government and industry standards. The guidelines recently issued by FEMA for lidar-derived DEM/DTM for hydraulic modeling and flood studies (FEMA, 2000) indicate the new level of recognition of lidar mapping technology as a valuable tool in providing cost-effective and accurate data for disaster mitigation government programs.

7. CONCLUSIONS

The lack of widely accepted standards for lidar system characterization leaves room for uncertainties and differences in interpretation of common terms, which may in turn lead to misinterpretation of the instrument performance capabilities. Because of these uncertainties, system specifications must be carefully analyzed and the use of different terminology should be taken into account. The new enhanced accuracy model of the ALTM 3100 system enables users to achieve higher relative accuracies for demanding large-scale mapping requirements. However, a knowledgeable and educated user should differentiate between the quoted performance specifications and the final accuracy of the lidar data. A thorough analysis of the system specification sheet, careful consideration of the optimal operational conditions, and appropriate selection and knowledgeable use of the data processing tools will help to reduce the gap between the performance specifications claimed by the manufacturer and the quality of the lidar data expected by the end users. As interest in airborne lidar technology from government agencies and research institutions is growing, strong cooperation and open dialog connecting them with the system manufacturers and service providers in the commercial sector would be beneficial to establishing a widely accepted quality standard for lidar-derived end products.

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