Accuracy Evaluation of LIDAR-Derived Terrain Data for Highway Location

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ABSTRACT

Surface terrain information is required to economically site new or relocate existing infrastructure facilities and make final design plans. Currently, ground surveying and photogrammetric mapping are the methods used by DOTs to acquire this data. Both methods are time and resource intensive since they require significant data collection and reduction to provide the level of detail necessary for facility location. Additionally conventional surveying entails data collection entirely in the field and may require that data collection personnel locate on or near heavily traveled roadways. Light Detection and Ranging (LIDAR) may provide an alternative technology to obtain terrain information in a more expedient manner. Data can be collected under a variety of environmental conditions including low sun angle, cloudy conditions, and even darkness, resulting in expanded windows for data collection. The research presented examines the elevation accuracy of LIDAR as it compares to a set of GPS control points on varying surfaces. This allowed for a determination of which surfaces LIDAR performed well on, as well as surfaces it did not.

INTRODUCTION

Highway location/relocation studies require surface terrain information to economically site new or relocate existing infrastructure facilities and make final design plans. Currently, ground surveying and photogrammetric mapping are the methods used by DOTs to acquire this data. Both methods are time and resource intensive since they require significant data collection and reduction to provide the level of detail necessary for facility location. Photogrammetry, the most commonly used form of data collection on large projects, is the most constrained by factors such as weather and sun angle. Additionally, conventional surveying methods entails data collection entirely in the field, which is labor intensive, time consuming, and may require that data collection personnel locate on or near heavily traveled roadways.

Light Detection and Ranging (LIDAR) may provide an alternative technology to obtain terrain information in a more expedient manner since it does not face the same limitations as traditional data collection methods. LIDAR data can be collected under a variety of environmental conditions, including low sun angle, cloudy conditions, and even darkness, resulting in expanded windows for data collection. Once data are collected in the field, data reduction can be accomplished fairly rapidly in comparison to photogrammetry.

BACKGROUND

Three collection methods are currently used by DOTs for large scale elevation data collection: Electronic Distance Measurement methods (Total Station), Real Time Kinematic (RTK) methods (GPS), and photogrammetry. EDM and RTK GPS methods require personnel to collect data in the field, while photogrammetric mapping is performed in the office.

EDMs transmit a light, laser or radio beam to a reflector that is held at a point distant from the device where measurement of a distance is desired (*1*). The reflector reflects the beam back to the transmitter and the difference in phase between the transmitted and reflected wave is measured electronically to determine the distance between the transmitter and the reflector (*2*). The microprocessor contained in the unit is capable of determining a variety of information, including coordinates (X,Y, Z), which define surface terrain.

RTK GPS surveys collect elevation and coordinate data using GPS receivers. Kinematic GPS uses carrier phase observations processed (corrected) in real-time to determine intersecting vectors (*3*). This produces measurements with centimeter or even millimeter accuracy (*4*).

Both EDM and RTK GPS methods share similar advantages and disadvantages, including:

Advantages:

- Electronic collection in field allows rapid download of data in office
- In-field presence allows notes to be taken
- Several units working independently allow for rapid data collection, especially in unobstructed areas (e.g. fields)

Disadvantages:

- Frequent equipment movements
- Permission required to access private property
- Personnel may work in hazardous areas (e.g. near roadways)
- Ineffective in areas where signals can be blocked (Forests, cities, etc.)

The third method utilized by DOTs for obtaining elevation data is softcopy (digital) photogrammetry. Photogrammetry is defined as the art and science of acquisition, measurement, interpretation and evaluation of photographs, imageries and other remotely sensed data (*5*). It is most useful in performing measurements of horizontal distances and elevations. In softcopy photogrammetry, digital raster images are utilized (rather than hardcopy aerial photos) to perform photogrammetric work (*4*). Instead of producing hard copy aerial photos, imagery taken during a flight is processed through high-resolution scanners to produce digital images. The digital nature of the data allows terrain mapping to be accomplished in an efficient manner through automation.

Advantages:

- Allows for large area mapping
- Property access issues eliminated
- Visual record of area created

Disadvantages:

- Highly trained personnel required to perform specialized techniques
- Limited data collection windows (Leaf-off, 30º sun angle, cloud free skies, etc.)
- Large collection areas required to be cost efficient (30 to 100 acres) (*2*)

LIDAR

The most significant disadvantage of current data collection methods is that a significant amount of time is required either in the field to collect (EDM and RTK GPS) or in the office (photogrammetry) to reduce the data. However, an emerging remote sensing technology, Light Detection And Ranging (LIDAR), has shown promise for collecting terrain information more rapidly than the existing data collection techniques. LIDAR is an active remote sensing system that utilizes a laser beam as the sensing carrier (*6*). Laser scanners measure three-dimensional points that are distributed over the terrain surface and on objects rising from the ground (*7*). Recent advances in LIDAR systems have reduced size, weight, and power requirements, while the accuracy of essential GPS systems has improved. Furthermore, advances in computer memory and processing speeds now allow vast quantities of data collected by LIDAR to be stored and processed more quickly and efficiently.

An aerial platform (usually an airplane) has a laser ranging system mounted onboard, along with other equipment including a precision GPS receiver and accurate Inertial Navigation System (INS) to orient the platform (*8*). The aerial platform is flown over the data collection area while the laser scans the area. The lasers utilized in this process typically emit thousands of pulses (up to 25,000) per second while in use. The travel time of these pulses is timed and recorded between the platform, the ground, and the platform once again (round trip), along with the position and orientation of the platform to determine range (distance) (*9*). From these distance measurements, elevations can be derived. Digital aerial photography can also be collected at the same time as LIDAR data, providing an additional layer of data, assuming conditions such as cloud cover are favorable. Figure 1 illustrates the LIDAR data collection process.

The majority of commercial organizations that collect LIDAR data state that the vertical accuracy of their data is generally on the order of 15 centimeters. However, a number of studies have examined the vertical accuracy of LIDAR data, with varying results. Most studies reported on LIDAR data that were collected under leaf-off conditions (*8, 9, 10, 11, 12*). Past research has also examined the accuracy of LIDAR data collected under leaf-on conditions (*13*). Table 1 summarizes the results of these research efforts. The variations in the accuracies achieved by these studies can be attributed, in part, to the differences between laser systems employed, flight characteristics, and the terrain being surveyed. As shown, accuracy ranged from 3 to 100 centimeters, with the majority of the studies reporting from 7 to 22 centimeters. These comparisons were performed in a number of ways, including point to point, point to LIDAR-DTM, and bilinear interpolation of LIDAR points to reference points.

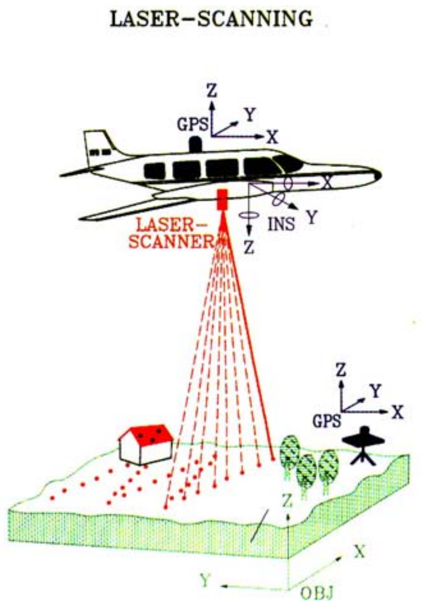

Figure 1: LIDAR data collection process
(Image source: http://www.sbgmaps.com/lidar_technologies.htm)

Table 1. Comparison of LIDAR Accuracy

Application	**Vegetation**	**Vertical Accuracy (cm) (RMSE)**
Road Planning (*10*)	Leaf-Off	8 to 15 (flat terrain), 25 to 38 (sloped terrain)
Highway Mapping (*9*)	Leaf-Off	6 to 10 (roadway)
Coastal, River Management (*14*)	Leaf-Off	18 to 22 (beaches), 40 to 61 (sand dunes), 7 (flat and sloped terrain, low grass)
Flood Zone Management (*11*)	Leaf-Off	7 to 14 (Flat areas)
Archeological Mapping (*12*)	Leaf-Off	8 to 22 (Prairie grassland)
Highway Engineering (*13*)	Leaf-On	3 to 100 (Flat grass areas, ditches, rock cuts) * Direct comparison to GPS derived DTM

Table 2 presents the required accuracies of mapping products as specified by the United States Geologic Survey (USGS). These are the accuracies required by the Iowa DOT for the photogrammetric products currently used for location and design activities.

Table 2.Iowa DOT accuracy requirements for photogrammetry products
Source: Iowa DOT

Photo Scale	Horizontal Error	Vertical Error
1"=250'	1.25 feet	0.30 feet (9 cm)
1"=333'	1.25 feet	0.30 feet (9 cm)
1"=500'	2.5 feet	0.50 feet (15 cm)
1"=1000'	5.0 feet	1.00 feet (30 cm)

RESEARCH OBJECTIVE

The focus of this research was to determine how accurately LIDAR performed in comparison to GPS data on different surface types. In order to make this determination, LIDAR data was compared to GPS data, which served as the "control". Such an evaluation would assist state DOT's in determining whether the accuracy of LIDAR data is suitable for the needs of highway planning and design. If LIDAR data proved to be accurate enough, it could serve as a supplemental form of data collection to existing methods, specifically photogrammetry, in the preliminary stages of route location and design.

STUDY AREA DESCRIPTION

To evaluate the accuracy of LIDAR derived terrain information compared to data derived from photogrammetry, a study corridor was selected. The main requirement for the study corridor was that it was an existing DOT project where photogrammetry work had been completed and that data had been collected within the last 2 to 3 years. It was thought that data collected in excess of that time period might not reflect current conditions. The Iowa Highway 1 corridor through Solon, Iowa, was selected for this study, as it met these requirements.

Iowa 1 is a two lane, undivided state highway running in a north-south orientation, located in the east-central portion of the state. The corridor is approximately 18 miles long, with photogrammetric data being produced for an area covering 10 square miles. The study segment begins at an interchange with Interstate 80 near Iowa City, and runs to a junction with U.S Highway 30 outside the town of Mount Vernon. The highway passes through the town of Solon, location of a proposed bypass, at about the midpoint of the corridor.

The corridor itself passes through a variety of areas and terrain. The southern portion of the route passes through rolling farmland. At the midpoint of the study segment, the highway passes directly through the town of Solon. A few miles to the north of Solon, Iowa 1 crosses the Cedar River, producing some distinct elevational changes. Figure 2 displays the Iowa 1 corridor.

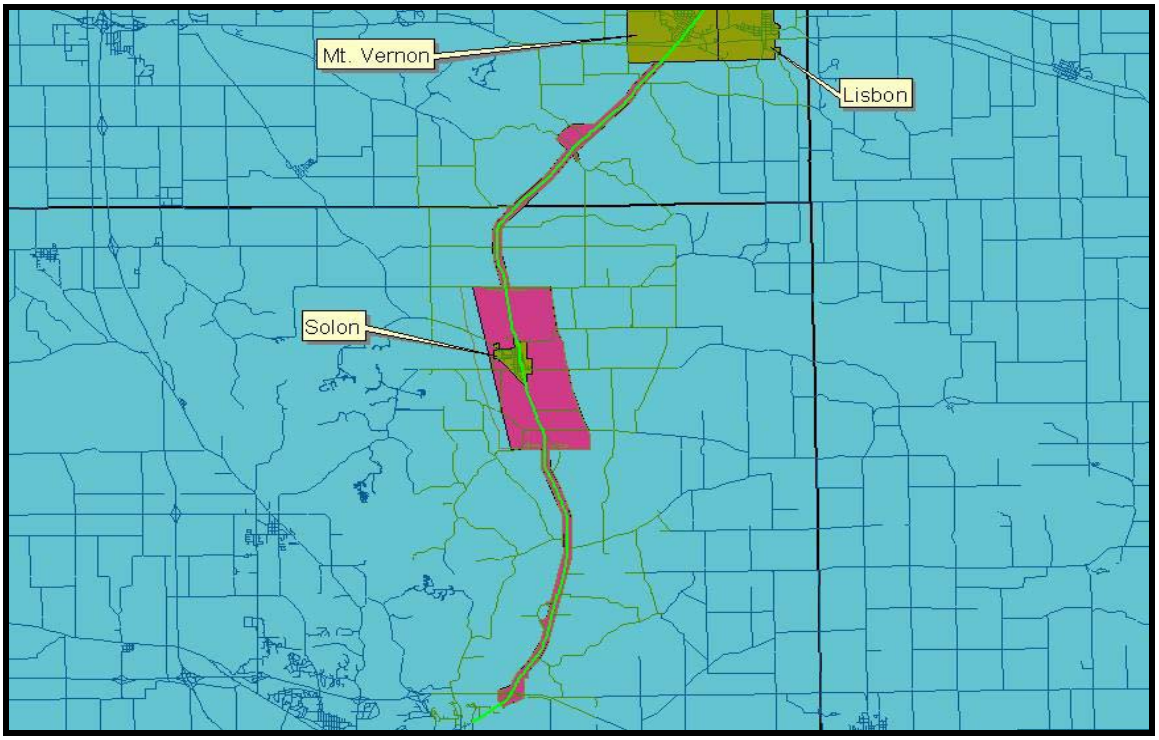

Figure 2: Iowa 1 Corridor

DATASETS

LIDAR data for the study corridor were collected in October of 2001. The vendor provided a LIDAR derived digital elevation data in the form of a point cloud consisting of an easting, northing and elevation (XYZ) with an average spacing of 2 meters. Three datasets were provided: First Return pulses, Last Return pulses, and Bare Earth. To produce a bare earth Digital Elevation Model (DEM), last return LIDAR pulses were processed with vegetation filters. Later work by the vendor produced a gridded DEM of 5 feet. All DEM data were delivered in comma delimited ASCII format.

The laser unit utilized by the vendor sent out 4000 pulses per second and scanned across the aircraft's flight path. Additionally, GPS and Inertial Measurement Unit (IMU) data were collected to record the aircraft's position, as well as its roll, pitch and yaw at the time each pulse was fired by the laser. Digital orthophotos of 1-foot resolution, with a horizontal accuracy of 2 meters were also collected during a separate flight from the LIDAR data collection. Imagery was orthorectified using airborne GPS data, platform attitude (pitch and yaw), and LIDAR DEM data. All data were projected in the Iowa State Plane South coordinate system. The horizontal datum was NAD83, and the vertical datum was NAVD88, with units in meters. Because LIDAR was flown in late fall, significant vegetation was still present. Harvesting of corn and soybeans, the two crops present in fields adjacent to Iowa 1, had commenced. As a result, some fields were harvested and others were not. This provided an unique opportunity to compare data for both leaf-on and leaf-off conditions.

High accuracy GPS data was also collected and used to compare both the LIDAR and photogrammetry for a limited subset of the corridor. In April of 2002, a consultant was hired to collect 177 GPS points at various locations throughout the study corridor to validate the accuracy of both the LIDAR and photogrammetry datasets. All data were projected in the Iowa State Plane South coordinate system, NAD83, NAVD88, and GEOID96. The vendor determined that the average elevation accuracy of these data was 1.21 centimeters.

STATISTICAL TESTS

The vertical accuracy of LIDAR data can be influenced by the type of laser system employed, the measurement process used, and the terrain itself (*10*). It can also be influenced by the acquisition and processing strategy of the vendor (*10*). Filtering procedures can also have an effect on the vertical accuracies of LIDAR (*13*). However, determining the influence of these factors was not part of the scope of this research.

To evaluate the accuracy of a dataset, a comparison must be performed. A dataset's accuracy is evaluated by comparing the coordinates of several points, which are locatable easily in all the dataset(s) with an independent dataset of greater accuracy. For this research, LIDAR data were compared to a photogrammetric dataset, as well as additional GPS points collected separately. The National Standards for Spatial Data Accuracy (NSSDA) recommends that points found at right-angle intersections such as roads, railroads, canals, utility access covers, and sidewalk and curb intersections be used for this evaluation (*15*). However, because LIDAR data are so dense and randomly distributed, identifying points that fall directly on such features would have been time consuming, if not impossible. Instead, a Grid Comparison method was used to develop grids of various resolutions. Points in these grids were extracted and compared to one another to perform accuracy assessments.

National Standards for Spatial Data Accuracy

The NSSDA outlines a statistical testing methodology for estimating the positional accuracy of digital geospatial data with respect to georeferenced ground positions of higher accuracy (*16*). This test applies to any georeferenced digital geospatial data derived from sources such as aerial photographs, satellite imagery and ground surveys. Twenty or more test points are required to conduct a statistically significant accuracy evaluation, regardless of the size of the data set or area of coverage (*15*). This also allows for the reasonable computation of a 95 percent confidence interval, meaning that, when 20 points are tested, it is acceptable that one point may exceed the computed accuracy (*15*).

To perform the accuracy comparison between LIDAR and photogrammetry, as well as GPS points, an adaptation of the recommended NSSDA methodology was utilized. The steps are as follows:

1. Determine what accuracy (horizontal, vertical, or both) is to be tested. In this research, only vertical accuracy was tested.

2. Select an independent dataset of higher accuracy that corresponds to the data being tested. In this research, the first independent dataset was the GPS dataset. The second independent dataset was the photogrammetry data previously produced for the Iowa-1 corridor.
4. Select a common set of test points from each of the datasets being compared. The Grid Comparison method was used to select points and LIDAR was evaluated for different types of surfaces present in the study area (hard surface, fields, etc.).
5. Calculate the positional accuracy statistic using an RMSE test.

RMSE Test

The test used to evaluate vertical accuracy was the Root Mean Square Error (RMSE) test. The RMSE test estimates the common within-group standard deviation of data. The test statistic is of the form:

$$\mathrm{RMSE}_z = \sqrt{\frac{\sum\left(X_{\text{ground value, i}} - X_{\text{test value, i}}\right)^2}{n}}$$

Where

$X_{\text{ground value, i}}$: ground truth point of the i^{th} point in the dataset

$X_{\text{test value, i}}$: test point of the i^{th} point in the dataset

$\sum\left(X_{\text{ground value}} - X_{\text{test value}}\right)^2$: sum of the set of squared differences between the ground and test data

n : total number of test points

To determine the NSSDA accuracy statistic, the RMSE value derived from the above calculation is multiplied by a value that represents the mean at the 95 percent confidence level (*15*). For vertical accuracies, this value is 1.96 (for horizontal accuracies, the value is 1.7308). The accuracy statistic is calculated with the following equation:

$$\mathrm{NSSDA} = \mathrm{Accuracy}_r = 1.96 * \mathrm{RMSE}_z$$

ACCURACY COMPARISON METHODOLOGY

The technique selected to compare elevations was a Grid Comparison. LIDAR data were interpolated into a 1-meter grid through Inverse Distance Weighted (IDW) interpolation. IDW interpolation assumes that the closer together slope values are, the more likely they are to be affected by one another *(17)*. Unlike triangulation, where points are simply connected together to form a surface, gridding mathematically computes the elevation values for the gaps that exist in the data. The LIDAR grid was developed using ArcView GIS and its Spatial Analyst extension. This extension allowed for the specification of output grid cell size to be made, as well as how many neighboring points could be used to influence the calculation of a grid cell elevation. For this research, twelve neighboring points were used for the calculation of the interpolated grid.

LIDAR points were densely spaced (1-2 meters on average), while GPS points were sparser. The result was an abundance of LIDAR points with which surfaces could be derived, while fewer GPS were available to generate a representative surface. To account for this problem, LIDAR points were interpolated into a grid, and then GPS points were overlaid on this grid. Using an ArcView script, the elevation values for the LIDAR grid cells underlying the GPS points were extracted for direct comparison.

RESULTS

Surface	No. Of Points	Mean Elevation Difference (m)	RMSE (m)	NSSDA (m)
Hard	66	0.113	0.336	0.659
Ditch	25	0.430	0.656	1.285
Slope	10	0.217	0.465	0.912
Rolling Terrain	24	0.110	0.331	0.649
Harvested	25	0.030	0.174	0.342
Unharvested	23	0.198	0.444	0.871

Table 2: LIDAR Accuracy Comparison Results

It was expected that LIDAR would be the most accurate on hard surfaces such as roadway pavements and parking lots. This was not the case however, as harvested fields produced a more accurate surface representation than hard surfaces. Overall, the computed RMSE values of LIDAR elevations on hard surfaces were not found to be accurate on hard surfaced areas. The RMSE value of LIDAR on hard surfaces (0.336 m) does not approach the 9 cm accuracy of photogrammetry produced from high-resolution imagery (although LIDAR does near the accuracy of photogrammetry products produced from lower resolution imagery).

LIDAR performed particularly poorly in ditch areas. This was to be expected, as the distribution of LIDAR pulses creates the potential for key features such as the top and toe of the ditch to be missed. Refer to Figure 3 for a schematic of this occurrence. The RMSE achieved by LIDAR (0.656 m) does not approach the accuracy of photogrammetry products produced from any resolution of imagery.

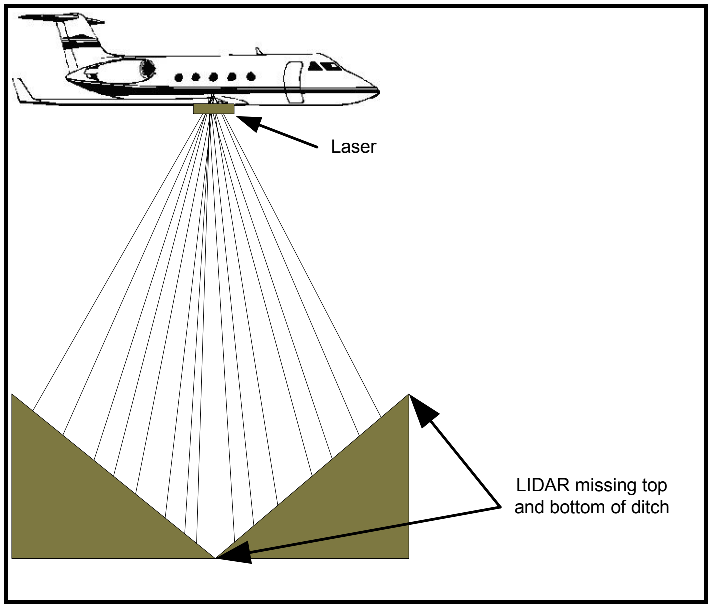

Figure 3: LIDAR pulses missing top and bottom of ditch

LIDAR performed more accurately on areas of slopes compared to ditches. The true steepness of such slopes (e.g. grade) was not collected, only spot elevations occurring on areas of lesser slopes (e.g. creeks). LIDAR still performed poorly in comparison to photogrammetry standards in these areas compared to other surfaces, producing an RMSE of 0.465 m. This could once again be attributed to the potential for LIDAR to miss sections of slope where abrupt terrain changes occur, such as the true bottom of a slope (see Figure 3). The result is less accurate surface model being created and producing significant accuracy differences.

On surfaces of rolling terrain, in this case a golf course, LIDAR produced results comparable to those produced on hard surfaces. The RMSE of LIDAR on rolling surfaces was 0.331 m, which was fractionally better than hard surface RMSE (0.336 m). However, the accuracy of LIDAR on rolling surfaces still did not approach the 9 cm accuracy of photogrammetry produced from high-resolution imagery. However, LIDAR accuracy did near the accuracy of photogrammetry products produced from lower resolution imagery on rolling surfaces.

On harvested surfaces (those from which crops had been cut before LIDAR data collection), LIDAR appeared to yield the best accuracy of any surface examined, with an RSME of 0.174 m. This RMSE value begins to approach the necessary accuracy of 9 cm required for highway planning and design activities. In fact, the RMSE value of LIDAR on harvested surfaces exceeded the required accuracy achieved by 1”=1000’ photogrammetry (30 cm) and nearly equaled the accuracies achieved by 1”=500’ photogrammetry (15 cm). The results produced on hard surfaces were surprising, given that such surfaces do not have the same hard flat surface characteristics possessed by roadways. One possible explanation for the greater accuracy achieved in harvested fields is that such areas possess different reflectance qualities than those present on hard surfaces. This difference in reflectance may produce different signal return times, leading to more accurate elevation measurements.

Unharvested surfaces included areas with corn and soybeans which had not been harvested when LIDAR data were collected. Results show that LIDAR did not perform adequately in areas of vegetation, as evidenced by the calculated error of 0.444 m. This value demonstrates that LIDAR pulses are not currently capable of penetrating dense foliage, such as corn and soybeans, and returning a true elevation of the earth's surface. While further filtering aids in the removal of such dense vegetation, the poor performance of LIDAR to initially penetrate crop canopy illustrates that such data collection might be more feasible under leaf-off conditions or when crops are in earlier stages of growth.

CONCLUSIONS

Accuracy evaluations of LIDAR show that the technology is not yet capable of replacing photogrammetric data in the final design of alignments. However, less accurate LIDAR data may still prove useful in expediting the location process. With LIDAR terrain information available to designers much sooner, preliminary analysis of study areas can commence. Initial terrain data collection would not be as dependent on environmental conditions (sun angle, cloud cover), since LIDAR is not affected by such conditions in the same manner as photogrammetry. Aerial imagery for the study area can then be collected at the same time or later as feasible. This would allow data to be collected more days throughout the year. The increased availability of data would allow terrain to be analyzed earlier in the location process, with potential problems identified and addressed at an earlier time.

It should be noted that the LIDAR for this research were colleted with full leaf-on, and presence of row crops in the final bare earth datasets demonstrates that LIDAR pulses are not capable of penetrating thick vegetative cover and hitting the earth's surface. While the presence of vegetation may not pose a problem for some applications, it does pose a problem in location and design functions, as true bare earth representations are required for design plans. The presence of vegetation produces a false representation of the true elevation in the field, which would subsequently lead to overestimations of items like cut and fill quantities. Consequently for best results, collection of LIDAR data should be avoided under conditions when dense vegetation is present. This also limits the time that LIDAR can feasibly be collected but still offers a much wider window than aerial photogrammetry.

The statistical evaluations performed show that LIDAR data collected under leaf-on conditions performs best in areas which lack vegetation, such as fields where no crops are present or, to a lesser extent, hard surfaces and rolling terrain. These are areas where there are no surface obstructions preventing LIDAR pulses from reaching the earth's surface. On surfaces with obstructions or dramatic terrain variability, such as unharvested fields, ditches and slopes, LIDAR performs poorly. This is attributed to the inability of LIDAR pulses to penetrate dense vegetation, as well as the potential for key features such as the top and toe of the ditches and slopes to be missed.

Preliminary research suggests that LIDAR data is best suited for providing designers with general terrain information early in the location process with which to identify final corridors where more intensive photogrammetric work can be performed. In this manner, the utilization of LIDAR data collection could produce time and cost savings by allowing expedient data collection to occur on a large corridor scale, with only limited areas being mapped by more time consuming and costly means. However, key design information, specifically breaklines, will not be available to designers.

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