

INFLUENCE OF VARIOUS PARAMETERS ON THE ACCURACY OF LIDAR GENERATED PRODUCTS FOR HIGHWAY DESIGN APPLICATIONS

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ABSTRACT

This paper addresses the influence of various parameters in the planning, data collection, post processing and related data adjustment processes on the accuracy of the LiDAR generated products for highway design applications currently being performed at the Ohio DOT. Some of the items discussed include base station distance, flight pattern design, and GPS attributes essential to the LiDAR collection process. In addition, of particular significance are the variables related to the thinning aspects of the LiDAR point cloud needed to reduce file sizes without degrading the quality of the final product. The reduced LiDAR data, consisting typically of ground points only, can be more efficiently adjusted to specific LiDAR control points in order to achieve maximum accuracy. With a TIN (Triangulated Irregular Network) being the primary deliverable for the designers, a vertical comparison of the TIN to the LiDAR control is performed to assess the accuracy of the TIN and other deliverables with a specific emphasis on the roadway areas.

INTRODUCTION

The Ohio Department of Transportation (ODOT) performs digital mapping as a part of the development process for highway improvement projects. Conventional practice utilized airborne photography to obtain planimetric and topographic features. While using photogrammetry to perform mapping can yield very good results, it is constrained by the requirements for obtaining suitable aerial photography. The constraints for film based aerial photography (for design mapping purposes) include leaf-off, minimal cloud cover, and sufficient light in order to produce appropriate images that allow identification of the ground surface. These constraints significantly limit the number of days that aerial photography operations can be performed in Ohio. In addition, the vertical accuracy on hard surfaces such as pavement was less than that desired by the design engineers given that the typical flying height was 1500 feet (AGL) for design mapping operations. Furthermore, it was very labor intensive to generate a large number of surface points. In an effort to improve vertical accuracy and increase the operational envelope under which terrain data could be collected, ODOT acquired an airborne LiDAR system (Optech ALTM 30/70) in 2004. Since implementation, ODOT has used the LiDAR system to create digital terrain models (DTM's) for both planning and design applications. This paper addresses the influence of various parameters on the accuracy of LiDAR generated products for highway design applications that require higher accuracy.

MISSION PLANNING

There are many parameters of the mission planning process which have an effect on the characteristics of the final product. Given the objective is a design application, the primary goal is to obtain adequate surface definition initially as uniform in each direction (both longitudinal and transverse to the line of flight) as possible. In order to achieve the needed definition, the point distribution and density sufficient to delineate the existing surface is of paramount importance. The point distribution and density are dependant on parameters such as the flying height, aircraft velocity, scan angle, scan frequency and pulse frequency. Obviously, the sensor parameters such as the scan angle, scan frequency, and pulse frequency are a function of the system capabilities.

Sensor Settings

The pulse frequency is always set to 70 kHz as a result of previous testing by ODOT which indicated the higher pulse rate (for this unit) generated data quality equal to the lower pulse settings of 50kHz or 33 kHz (along the pavement surface). The scan angle is set at +/- 20 degrees (40 degree FOV) resulting in a swath width of approximately 1,100 feet. The scan frequency is set at 50 Hz in order to create a relatively uniform point distribution with a post spacing of approximately 18 inches per pass, given the aircraft velocity is estimated at 100 knots.

Overlap

A side lap of 50% is used to double the point density of areas to be mapped resulting in an effective post spacing of approximately 13 inches. This point density has proven to be effective in delineating the surface for design projects. Even with this point density, the presence of some vegetation types can be an issue and may require additional surveying in order to meet the project specifications. An additional benefit of the overlap is that it can be used in the LiDAR strip alignment discussed in the data processing procedures.

Base Station Distance

During mission planning, the project site is located on a map and the distance to the closest CORS station is determined. Figure 1 shows the locations of CORS stations in Ohio operated by the Ohio Department of Transportation. The GPS baseline (distance to a CORS station or project specific base station from the aircraft) affects the quality of the GPS solution, and therefore the accuracy of the LiDAR point cloud. Figure 2 shows the effect of the baseline distance on the quality of the LiDAR solution by comparing the LiDAR data obtained by using different base stations with increasing distances. The LiDAR data produced by using the base station on the project site were used as the reference in the comparison. In Figure 2, the increased error in the vertical direction is shown with respect to the baseline distance.

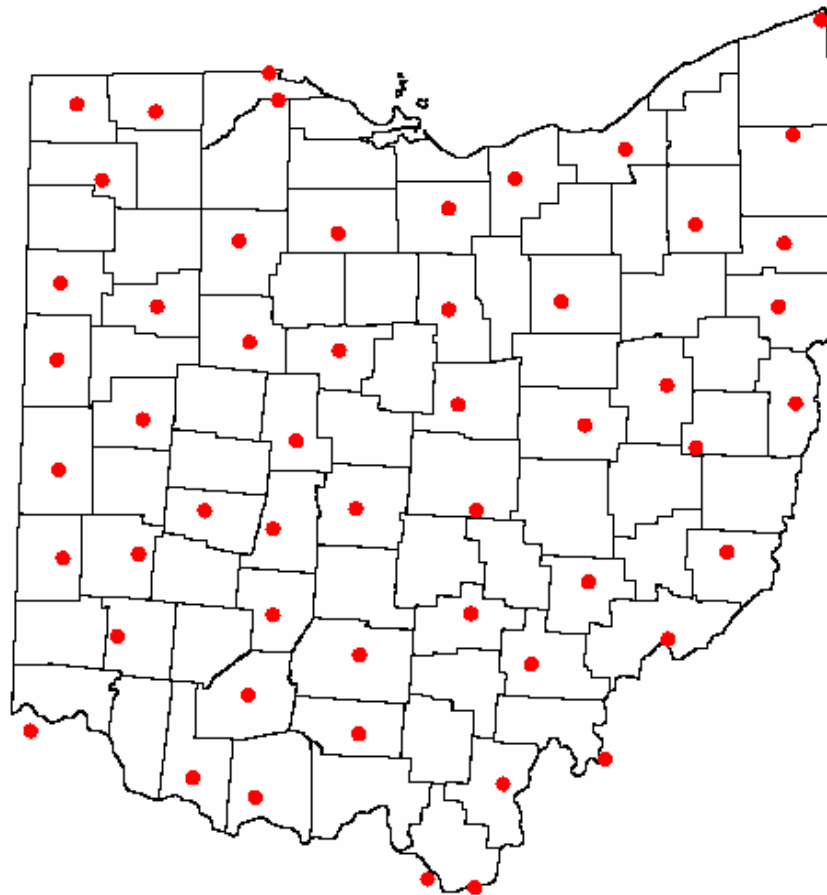


Figure 1. The Ohio Department of Transportation CORS Network with the location of the individual CORS stations shown in red.

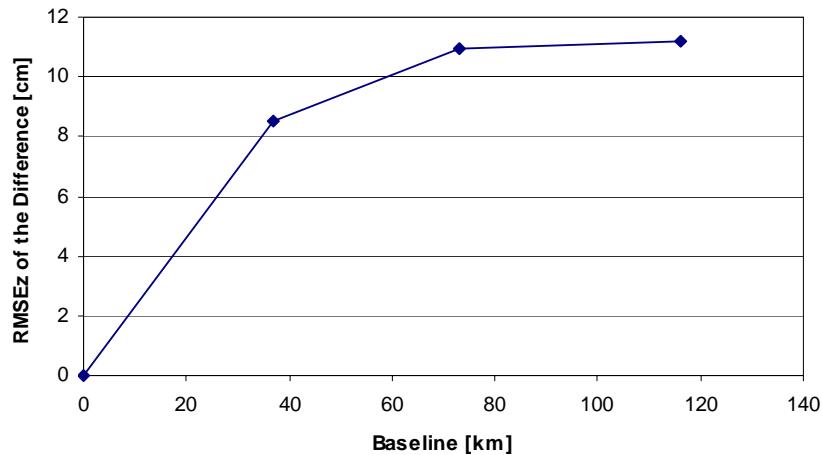


Figure 2. Baseline distance dependency on LiDAR solution accuracy

Based on this information, ODOT typically plan to set up a base station in addition to the existing CORS stations when the distance from the job to a CORS station exceeds about 15 km in order to maintain the quality of the GPS/INS data. Ideally, the base station would be set up at the center of the project area.

Flight Pattern

The flight lines over the project area are planned and delineated in ALTM NAV (a software product by Optech), then uploaded into the LiDAR system on the aircraft. Because most projects are a significant distance from the “home” airport, typically an in-air IMU initialization is performed. In short, this involves flying straight and level approximately three minutes towards the base station and three minutes beyond the base station continuing on the same course. Additional aircraft maneuvers are made just before collecting the LiDAR data in order to maintain a high quality GPS/INS solution. It is essential to periodically exercise the IMU in order to compensate for any IMU drift. The LiDAR flight pattern itself is either flown in alternating directions or in the same direction depending on the flight line orientation, wind direction and velocity. The number and orientation of the cross flights are dependent on the size of the job, but are also dependent on the LiDAR flight pattern in order to make full use of the processing capabilities in TerraMatch (a TerraSolid product) to align multiple strips of data. Figures 3a and 3b above show the minimum cross flight requirements.

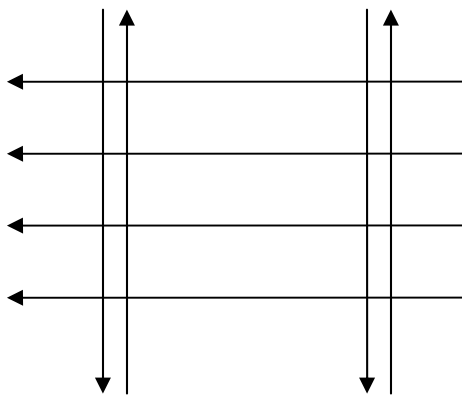


Figure 3a. Cross flights required for LiDAR strips flown in the same direction.

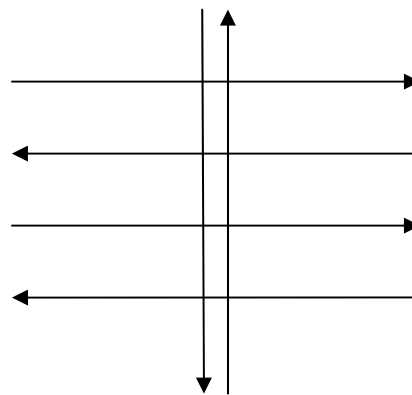


Figure 3b. Cross flights required for LiDAR strips flown in alternating directions.

GPS Attributes

As mentioned earlier, with the LiDAR data being GPS/INS controlled, the quality of the GPS/INS solution is paramount. At 1500 feet AGL, the GPS component of the navigation solution would typically be the governing

factor with the class of IMU is being utilized. Under normal conditions the PDOP (Positional Dilution of Precision) and the number of satellites visible above a specified mask angle would be examined prior to and during flight as an indication of the potential quality of the GPS/INS solution. The PDOP value (Leick, 1995) indicates the quality of the satellite constellation with lower values being desired. Figure 4 below is a plot of various dilution of precision indicators as a function of time for February 6, 2007 obtained from the Trimble Geodetic Office planning utility software. Clearly, there are specific time frames when the PDOP is substantially higher than others. In reviewing the effect of the PDOP on the LiDAR solution, we examine how well the LiDAR data compares to GPS-surveyed check points on the ground, classified as hard surfaces. Figure 5 shows the influence of the various PDOP values on the quality of the LiDAR solution. The data were obtained by comparing ground control points to the LiDAR point cloud processed with different PDOP values for the GPS data. The PDOP values were artificially increased by raising the mask angle for the same GPS dataset. Figure 5 shows that when the PDOP exceeds 3.0, the vertical difference with respect to the control points begins to increase significantly.

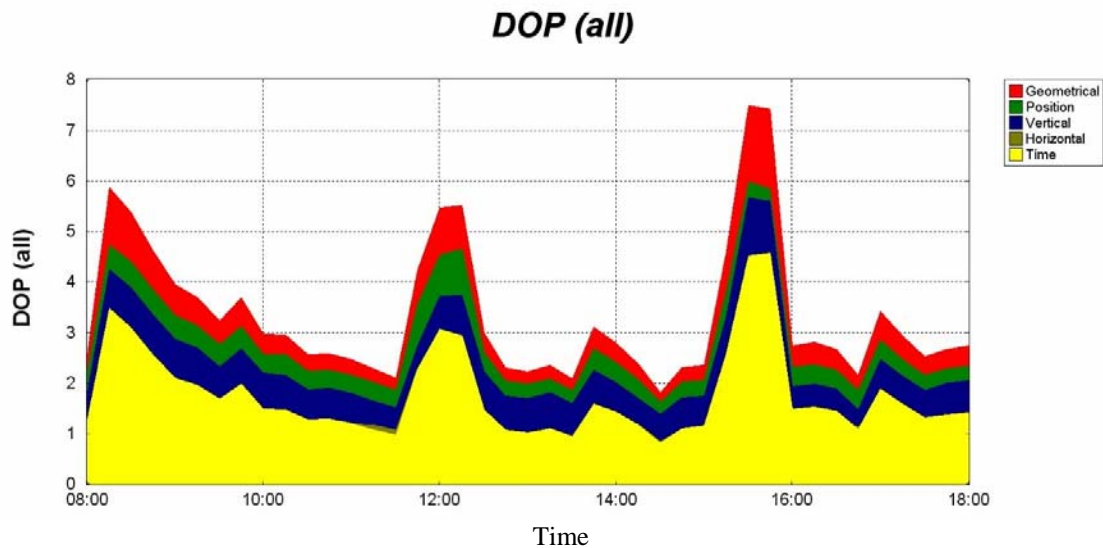


Figure 4. Various dilution of precision indicators for a ten hour time period.

Despite careful planning, the PDOP may change during flight, and therefore, the PDOP must be monitored in the aircraft to ensure a quality solution. While it is typically easier to track more satellites in the air versus on the ground (at a base station), aircraft maneuvers while performing flight operations can block the view of satellites (depending on the location of the GPS antenna) and instantaneously increase the PDOP. The most common situation is for the wing of the plane to block the signal of a satellite when making a turn involving banking. For this reason, the banking angle is normally limited.

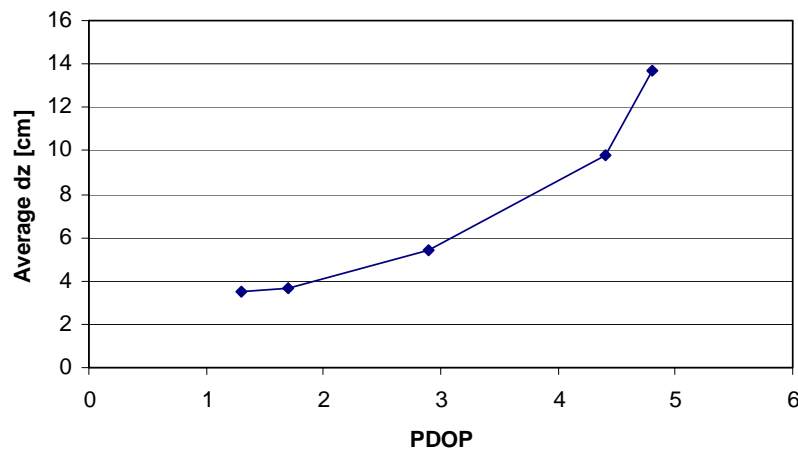


Figure 5. Influence of PDOP on LiDAR solution

Base Station Data

The CORS and project specific base stations are set to collect 1 Hz GPS data. The coordinates of the base station are computed in ITRF00 to allow time dependent coordinate transformations to be performed in accordance with NGS procedures. Note that the time dependent transformations account for tectonic plate movement which is estimated at 15 mm per year in a westward direction in Ohio.

LiDAR Control

LiDAR control is a series of ground points collected on “hard” surfaces at multiple locations within the project. For the majority of the design jobs, control profiles along the road and cross sections work well. The LiDAR control is used to check and adjust the LiDAR dataset to the ground truth as needed. LiDAR-specific ground control targets have also been used successfully (details in Csanyi et al, 2005). Note that “soft” surfaces are also collected at the same time as the “hard” surfaces and are used to indicate the accuracy of the mapped surface at the corresponding vegetation types.

DATA PROCESSING

Data Processing Workflow

The current workflow for processing the LiDAR data is shown in Figure 6 as sequential tasks optimized to maximize the quality of the final product. Intermediate products such as the LiDAR intensity image and a preliminary surface are generated as soon as possible to enable concurrent processing within the photogrammetry area for planimetric feature collection and creation of orthophotos.

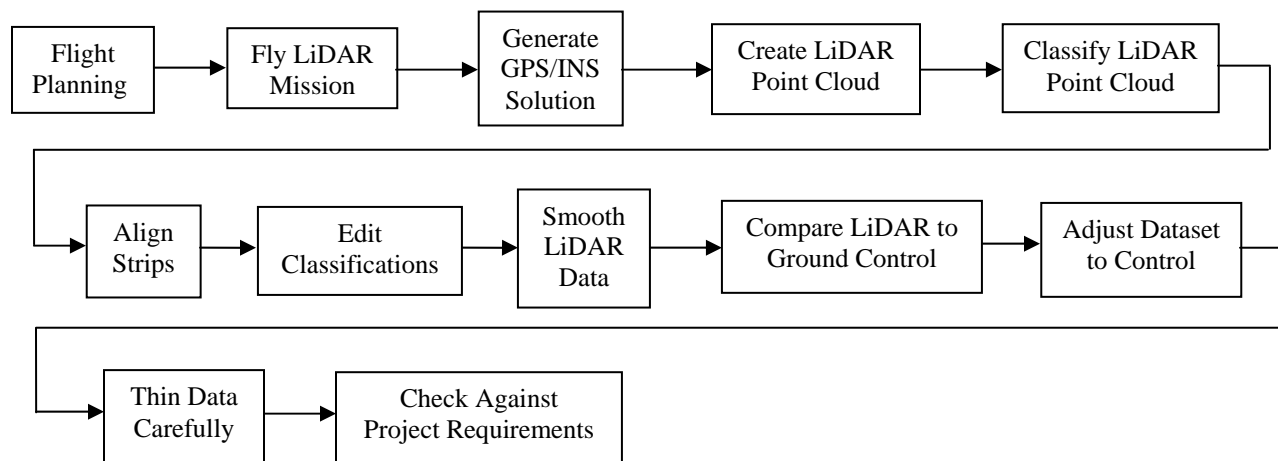


Figure 6. Data Processing Workflow

Datums, Coordinate Systems, and Transformations

To obtain the final product, the process utilizes many software packages during the various procedures. At different stages of the process, coordinate and datum transformations are performed. Table 1 summarizes the horizontal and vertical coordinate systems and datums with respect to the different processing tasks.

Both WGS 84 (see Table 2) and NAD 83 have been redefined several times since their inception. Similarly, there have also been several realizations of the International Terrestrial Reference System (ITRS), referred to as ITRFxx, where xx refers to the date. Therefore, it is important to thoroughly understand the different datum transformations that exist as well as their impact. Applying improper coordinate transformations can lead to confusion and unsatisfactory positioning results.

Table 1. Horizontal and vertical coordinate systems and datums with respect to the different processing tasks

Processing Tasks	Horizontal Component	Vertical Component
Base station coordinates	Geographic lat/lon Datum: ITRF00	Ellipsoid height Datum: ITRF00
Integrated GPS/IMU solution of the sensor trajectory	Geographic lat/lon Datum: WGS84 (G1150)	Ellipsoid height Datum: WGS84 (G1150)
Initial LiDAR point cloud	UTM, Zone 16 or 17 Datum: WGS84 (G1150)	Ellipsoid height Datum: WGS84 (G1150)
End products	Ohio State Plane Datum: NAD83 (CORS96)	Orthometric height (NAVD88)

Table 2. WGS84 Reference frame equivalents.

Reference Frame	Equivalent to
WGS 84 (original)	NAD83 (1986)
WGS 84 (G730)	ITRF92
WGS 84 (G873)	ITRF96
WGS 84 (G1150)	ITRF00
Note: WGS 84 (G1150) differs from NAD 83 (CORS96) by approximately 1m horizontally and 1.2m vertically.	

Strip Analysis and Alignment

With flying 50% overlap for the design applications, the LiDAR datasets always contain multiple strips even for small jobs. The multiple overlapping strips are analyzed in TerraMatch and viewed in GeoCue to determine if any vertical discrepancies between the LiDAR strips exist. This procedure is necessary because the data in overlapping areas are used, not discarded. The initial strip analysis normally reveals vertical alignment discrepancies in the 0.2 to 0.4 foot range. After the alignment routines are performed, the resulting vertical discrepancies typically average less than 0.10 feet. It should be noted that the vertical discrepancies in the raw data are well within the stated accuracies of the LiDAR system. Additionally, the strip to strip vertical differences appear to be a function of the GPS/INS solution and not the LiDAR sensor itself. Our perception is based on examining cross-sections of data from overlapping strips.

It is important to fully understand how any software works being used to compare the LiDAR dataset to check points on the ground (also known as LiDAR control). This issue may seem obvious, but the software creating the surface for analysis purposes, TerraMatch in our case, is not the same software used to create the final product. ODOT uses GeoPak as its design software, and therefore the final surface is created in GeoPak. For example, does the LiDAR processing being used for analysis create the surface (1) from the bottom upward, (2) from the top down, (3) using an average of the points, or some other method? This issue is critical for ODOT given that we adjust the data set (consisting of ground points) to the LiDAR control near the end of the processing.

Classification of LiDAR Points

The point cloud is classified using the TerraScan software with the following classes: ground, vegetation and miscellaneous, water, and bridges. The standard classification routines do a reasonably good job of properly assigning points to the appropriate classification. Note that both the water and the bridges classifications are manually separated. The point classifications are reviewed and edited to correct any noticeable or perceived classification errors.

Smoothing Points

Having the points properly classified, only the “ground” classified points are desired in the remainder of the processing to create an existing surface. Our experience has indicated that smoothing of the points on hard surfaces has a minimal effect on the quality of the end product.

Thinning Points

The thinning is performed in TerraScan to reduce the size of the files needed to create the end products. Care must be taken when performing thinning to ensure points necessary to define the surface are not eliminated, otherwise the accuracy will suffer. Thinning can obviously vary depending on the terrain, vegetation, point density and desired outcome which necessitates review of the thinning parameters on a project by project basis. The three cross-sections below show the impact of the thinning using different methodologies on the same dataset within a roadway area. Figure 7, Section (a) illustrates the original ground classified points. Section (b) shows the results of thinning by keeping only the “model keypoints”. Model keypoints are determined by the software in order to maintain a specified vertical accuracy while removing unnecessary points. By using the model keypoint function, the dataset was reduced by 58 percent while attempting to achieve a 0.05 foot accuracy with respect to the original points. Section (c) was generated by removing points from the original ground class which have other points within a radius of 6 feet and within 0.10 feet vertically (see TerraScan User’s Guide). This thinning resulted in a reduction of 78 percent of the original ground points, although a slight loss in accuracy begins to become apparent. For this reason, while thinning can substantially reduce the number of points and therefore the file size, one must be careful to ensure project requirements are still being fulfilled as thinning is being performed.

Adjusting Data to the LiDAR Control

The remaining points are used to create the TIN which is compared to the LiDAR control points. The analysis of the results enables a comparison between the dataset and the control. Any adjustments to improve the “fit” to the control are performed and the analysis is run again to ensure the end product meets the required specifications. After adjusting the dataset, the vertical RMSE is typically between 0.05 and 0.10 feet. It should be noted that only hard surface points are used to adjust the LiDAR dataset.

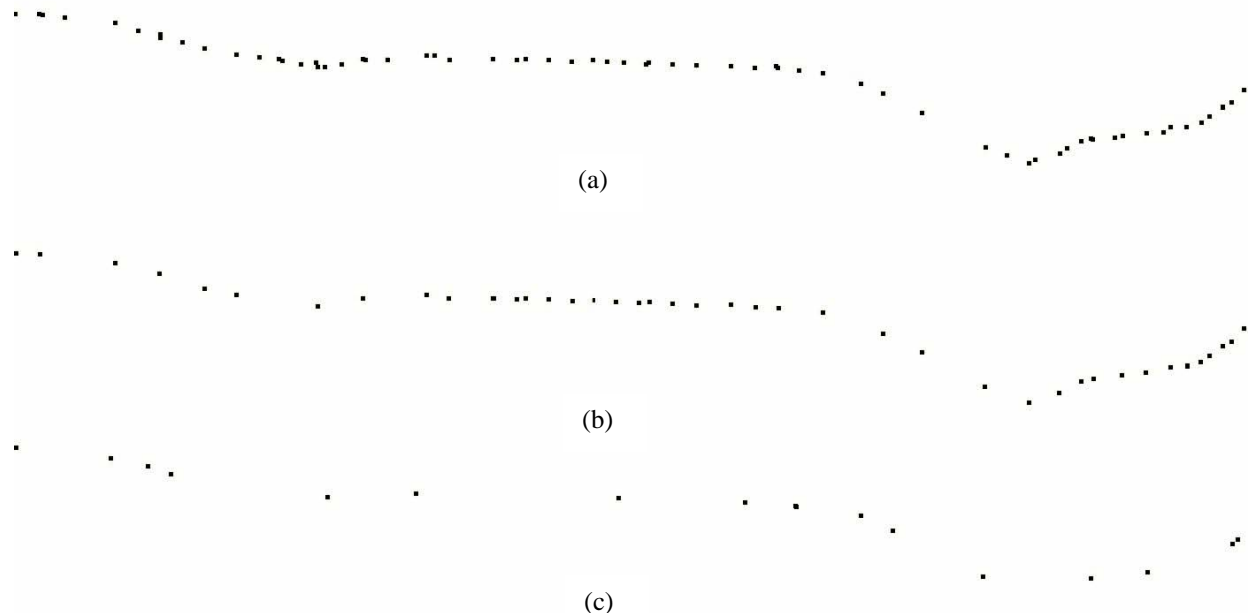


Figure 7. Ground classified points: (a) original, (b) thinned using model keypoints, (c) thinned using 6 foot radius and 0.10 feet dz parameters.

CONCLUSION

Almost every system and aircraft parameters can affect the accuracy of LiDAR generated products to varying degrees. The software being used throughout the entire process is one item that should be thoroughly examined to ensure any geodetic datum and coordinate transformations are properly handled in accordance with the National Geodetic Survey to avoid unnecessary accuracy related problems. Planning efforts can greatly aid in increasing accuracy by avoiding flight operations during time periods of high PDOP as well as minimizing the base station distance especially for longer jobs. The combined effect of the PDOP and base station distance on the accuracy can be significant. Being able to compare and adjust overlapping strips (and cross flights) of LiDAR data seems to work well in reducing vertical discrepancies within overlapping areas. Adjusting the LiDAR dataset to ground control obviously improves the accuracy due to the ground control being the basis of comparison and considered absolute. LiDAR surveying over certain types of vegetation can be problematic, however mowing where possible or supplementing with ground surveying such as real-time-kinematic GPS can provide cost effective solutions to achieve the desired accuracy. In summary, by paying close attention to several parameters during the planning, data collection, and processing operations, it is possible to generate LiDAR based products meeting the needs of our design applications on a routine basis.

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