3D Modeling of UC Berkeley's Strawberry Creek using Terrestrial LiDAR

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ABSTRACT

Riparian zones are an important indicator of ecosystem health. However, gathering data in these study sites can be challenging. The increased use of remote sensing technology such as aerial LiDAR have emerged as a way to help gather data in river ecosystems. Although marginally useful in riparian zones, aerial LiDAR also has its limitations, especially in areas where high vegetative cover blocks aerial LiDAR scanners from collecting data underneath the vegetation. In our study, we collected point data that was underneath the vegetation using a terrestrial LiDAR scanner. Our goal was to provide a blueprint for the use of terrestrial LiDAR scanning in stream riparian zones and to create a ground point model for Strawberry Creek so that we could understand its geomorphology. Through our use of a terrestrial LiDAR scanner to collect data for Strawberry Creek, we found it to be extremely important that the coordinate system the LiDAR scanner is collecting data in matches up with the coordinate system of the control points that will be used for georeferencing. In addition, having enough manpower and assigning tasks to everyone would have increased the efficiency of our data collection in the field. The ground point models we produced from the LiDAR scans created a complete ground model of the two natural areas. Overall, terrestrial LiDAR scanning can provide a tremendous amount of data that would be extremely helpful in assessing riparian streams.

KEYWORDS

Stream ecology, geomorphology, terrestrial LiDAR, Digital Elevation Models (DEMs)

INTRODUCTION

Remote sensing and its applications to ecology is an emerging field that could help answer many questions about the shape and processes of the natural world. One of the most common and widely used remoting sensing technologies is LiDAR, or Light Detection and Ranging. In this remote sensing technique, a laser scans an area and then constructs a map of the scanned area using billions of individual points (Jaboyedoff 2010). There two forms of LiDAR, a terrestrial version that is mounted on a tripod and moved from place to place and an aerial version mounted on an airplane, helicopter, or a drone (Jaboyedoff 2010, Chuang and Jaw 2017). LiDAR has mainly been used in engineering applications, where it has helped engineers construct buildings and bridges (Williams et al. 2013) and survey urban areas. Recently however, LiDAR has also spread to fields like forestry, where it has assisted in making tree measurements (Tilley et al. 2004, Dubayah and Drake 2000, Wulder et al. 2012, Lefsky et al. 2002), and archeology, where it helped find ancient Mayan structures beneath dense vegetation that would otherwise be invisible to the naked eye (Chase et al. 2014, Macrae and Iannone 2016, Chase and Chase 2017). In addition, there has also been applications of LiDAR in geology and ecology where it has helped monitor potential areas of gully erosion (Jaboyedoff 2010, Bremer and Sass 2012, Perroy et al. 2010, Wawrzyniec et al. 2007). Through all these different applications, LiDAR has consistently increased the accuracy of measurements by gathering measurements that could not have been made using traditional survey techniques.

Although there are tremendous benefits in using remote sensing approaches such as LiDAR to conduct research, there are also limitations. One key limitation is the cost of using a LiDAR scanner (Tilley et al. 2004, Wulder et al. 2012, Jakubowski et al. 2013) and the different software needed to analyze the data (Williams et al. 2013). Using a helicopter or a drone to carry an aerial LiDAR scanner can dramatically increase the cost of a project. In addition, software licenses are costly and may not always have all the necessary tools that are needed to process the data to gather specific measurements for a project. For example, some softwares are more useful in forestry applications of LiDAR while other softwares are more useful for engineering applications of LiDAR. This disparity results in files needing to be exported from one software and converted so that it can be compatible with another software that is more useful. Another key limitation is that aerial LiDAR cannot see through objects when scanning from the air. For example, thick vegetation can restrict aerial LiDAR, thereby limiting the information collected about the surface of the landscape (Jaboyedoff 2010, Bremer and Sass 2012, Murgoitio et al. 2013, Crow et al. 2007).

Areas with restricted resolution for these geomorphological characteristics include stream riparian zones that often have thick vegetation surrounding the stream. Stream riparian zones are an important area of research because they are areas that are very susceptible to pollution and need to be managed properly to ensure ecosystem health. One area of concern in stream riparian zones is the erosion along the stream banks that could affect water quality (Wood and Armitage 1997). Another concern is for flood control along the stream during wet winters which could damage infrastructure and landscape surrounding the stream. LiDAR has the potential to assist in making precise measurements to better understand the areas of potential erosion and to model flows for flood control. However, as a result of high vegetative cover, gathering accurate and useful data in stream riparian zones is very challenging for aerial LiDAR. One of the potential solutions to solve the inability for aerial LiDAR to be used in stream riparian zones would be to instead use terrestrial LiDAR to scan the area and gather the information that the aerial LiDAR could not.

The objective for this study was to create a 3D model of the Grinnell Natural Area and the Goodspeed Natural Area of Strawberry Creek on the UC Berkeley campus using terrestrial LiDAR scans. To create this model, a process for terrestrial LiDAR scanning was established for stream riparian zones. This established process would be useful as a reference for how future terrestrial LiDAR scanning could be completed in stream riparian zones. From these scans, a ground point only model was also established for each natural area. These ground point models will be able to help us better understand the geomorphology of the stream and to assist us in making future management decisions in Strawberry Creek.

METHODS

Study Site

Located in a Mediterranean climate with cool wet winters and hot dry summers, Strawberry Creek is an urban stream running through Berkeley, California. The source of the stream is in the Berkeley Hills in Strawberry Canyon. From Strawberry Canyon, the water moves downstream in a westward direction towards the UC Berkeley campus. There are two main forks of Strawberry

Creek, the North Fork and the South Fork. The North Fork flows through the campus passing through the Wickson Natural Area while the South Fork flows through the campus passing through the Goodspeed Natural Area (Figure 1). Both forks of the stream then continue through the campus until they confluence at the Grinnell Natural Area to form the main stem. Continuing downstream, the creek enters an underground culvert at Oxford Street before reappearing in a daylighted section in Strawberry Park in the City of Berkeley. It then enters another underground culvert which eventually debouches out into the San Francisco Bay.

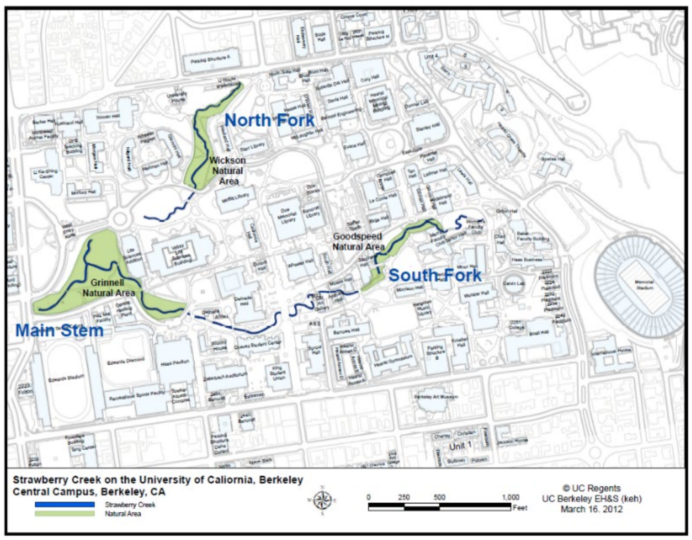

Figure 1. Map of Strawberry Creek flowing through the UC Berkeley campus along with corresponding Natural Areas that the creek passes through. (http://strawberrycreek.berkeley.edu/sites/default/files/scnaturalareas.pdf)

For this project, I focused on two areas of Strawberry Creek on the UC Berkeley campus, the Grinnell Natural Area and the Goodspeed Natural Area. The Grinnell Natural Area for the North Fork of Strawberry Creek begins southwest of the West Circle and the Grinnell Natural Area for the South Fork begins west of the octagon bridge, which is located on the south side of the Valley Life Sciences Building (Figure 1). In addition, the Grinnell Natural Area also includes the confluence area where the two forks of the creek meet and flow downstream towards Oxford Street. In the Grinnell Natural Area, Strawberry Creek is nestled in the middle of a large green area consisting of a large Eucalyptus grove with scattered coast redwoods. Vegetation along Strawberry Creek in this area varies from dense with heavily vegetated banks of Algerian Ivy to light with only fallen Eucalyptus or coast redwood leaves covering the banks. Canopy cover from the

Eucalyptus and the coast redwoods are high in the Grinnell Natural Area and result in little sunlight reaching the ground.

In the Goodspeed Natural Area, Strawberry Creek runs westward from the Men's Faculty Club to the south side of Stephens Hall. This area is populated with live oaks and scattered coast redwoods which provides an extremely dense canopy cover for the stream. The banks of Strawberry Creek in the Goodspeed Natural Area are also densely covered with Algerian Ivy with some areas being bare.

Data Collection

Terrestrial LiDAR Scanning Process

Terrestrial LiDAR Scanning of Strawberry Creek in the Grinnell Natural Area and the Goodspeed Natural Area were completed using a Trimble TX6 Scanner over 4 consecutive days beginning on March 17th, 2018. The Trimble TX6 Scanner has a field of view of 360 degrees horizontally and 317 degrees vertically. The only area that the scanner could not see was the area underneath it. See Figure 2a to visualize the structure of the scanner. Trimble TX6 has a scanning speed of 500,000 points per second and can scan a distance between 0.6 meters and 80 meters. However, the scanning distance is dependent on the reflectivity of the objects far away because objects with lower reflectivity will also be less intense, thereby making it harder to be scanned (Trimble Geospatial 2018).

To collect the terrestrial LiDAR data in the field, I had the help of my two mentors, Liam Maier and Patina Mendez, and two volunteers, Michelle Yang and Shannon Chang.

The first step in our data collection was to secure the Trimble TX6 Scanner on a tripod with the height of approximately 5 feet. For the first scan of Strawberry Creek in each Natural Area, we leveled the scanner with the bubble on the screen of the Trimble TX6. Next, we placed targets (Figure 2b) and spheres (Figure 2c) in positions that were within the line of sight of the scanner. The placement of these targets and the spheres needed to be in areas where they could be seen in the subsequent LiDAR scans taken as we move downstream along creek. Ideally there would be at least 4 targets or spheres in the current LiDAR scan that could be seen in the next LiDAR scan. See an example of the placement of the targets and spheres (Figure 2d). With these targets and spheres in multiple scans, we were able to connect all the individual scans to each other during the data registration process, thus producing a 3D digital model of Strawberry Creek.

At each scan location, two types of scans were taken. The first scan at each spot was a High Dynamic Range (HDR) image scan. This scan was a photo intake that provides color for the LiDAR scans. Each HDR image scan took approximately 2-3 minutes. Immediately after the HDR scans, the Trimble TX6 scanner would start the LiDAR scan. The LiDAR scan took approximately 6-7 minutes. TCF and a TZF files were created by our Trimble TX6 LiDAR scanner as it scanned the area. These files were the original files uploaded into the Trimble Realworks software for data registration and processing in order to build point clouds for each natural area.

During this scanning, the LiDAR scanner maps the terrain of the area around it and creates millions of individual points. These individual points at the scan station are then combined together to construct an 3D model of the scanned area.

After completion, the Trimble TX6 Scanner and the tripod were both moved approximately 3-4 meters downstream for the next scan. The placement of the scanner at the next location was dependent on the sinuosity of the stream. We looked for lines that were tangent to the curve and made sure that the targets and spheres from the previous scan were within the line of sight of the scanner. With the location of the next scan determined, more targets or spheres were added before the scanner was started again. However, we did not level the scanner every time because that was only required for a couple scans in each natural area. The Trimble TX6 Scanner was then started and the whole process started over again. We continued to do this along Strawberry Creek until we had a LiDAR scan for every part of the creek in the Grinnell and the Goodspeed Natural Areas.

In addition to the terrestrial LiDAR scanning of Strawberry Creek, we also wanted to add LiDAR scans of UC Berkeley control points near the creek so that we could tie the scans into the UC Berkeley campus coordinate system. By tying the LiDAR scans of Strawberry Creek to these campus control points, our LiDAR dataset would be able to be compared with other LiDAR (e.g. aerial) and map data collected from the same area. In the Grinnell Natural Area, we connected Strawberry Creek LiDAR scans to three control points (UCB 1621, UCB 1623, UCB 1631). In the Goodspeed Natural Area, due to time constraints, we were only able to connect our Strawberry Creek LiDAR scans to only one control point (UCB 1633).

Figure 2. a) A Trimble TX6 Terrestrial LiDAR scanner mounted on a tripod. b) A checkerboard target on a stake. c) A sphere on a control point. d) The Trimble TX6 Terrestrial LiDAR scanner with targets and spheres in its line of sight at the Grinnell Natural Area.

LiDAR Data Registration and Processing Techniques

Constructing Point-Clouds

Data registration was completed using the Trimble Realworks, a software designed to process and analyze 3D LiDAR scans taken with the Trimble TX6 terrestrial LiDAR scanner. First, we imported the all scans taken with the Trimble TX6 scanner from our flash drives. In Trimble Realworks, one project was started for the Grinnell Natural Area and another project was started for the Goodspeed Natural Area. The software then prompted us to create Sample Scans, which converted the scans taken in the field so that we would work and modify it in the software. These sampled scans reduced the number of points that were collected by the scanner in the field from more than 90 million to less than 20 million in most scans. Doing this reduction allowed the software to run faster without compromising data accuracy.

After importing the scans into the Trimble Realworks and creating the Sample Scans, we then attempted to build a point cloud for the Grinnell Natural Area. A point cloud is a 3D data model that is produced containing all the scans and their respective data points from an area. First, we attempted to register, or line up, the scans in the Grinnell Natural Area by the target and the spheres that we implanted during our LiDAR scanning in the field. The software looked for the same targets and spheres that were captured in different scans and tried to match these scans up with each other. The spheres were very helpful in matching the scans up together, however, this was not always true for the targets, which were sometimes more difficult for the software to find. Next, we used plane-based registration to combined the scans that weren't already matched up. Plane-based registration attempted to find all the data points that were in the same x-plane, in the same y-plane, and the same z-plane together. In addition, we also tried to use cloud-based registration to match up our scan stations. This series of steps matched up almost all the scans and the scans that were left were manually registered into the point-cloud. After doing this we did another cloud-based registration to group the scans so that we could visualize just one section of the natural area at a time. This process of data registration allowed all the scans in the Grinnell Natural Area to be combined into a single point-cloud. The same process was completed to register the data for the Goodspeed Natural Area.

After building the point clouds for the Grinnell and the Goodspeed Natural Area, we did a visual check looking through the point clouds to see if there were any errors present. One error that we had to manually edit out was an umbrella that we used to cover the scanner while it scanned the Goodspeed Natural Area in the rain. We manually selected the points that were the umbrella and deleted them from the point-cloud. Another error we noticed in the point cloud was in the Grinnell Natural Area where some of the scans did not line up with each other. This discrepancy resulted from a scan leveled at the wrong place in the point-cloud, so we used the software to force that single scan to unlevel. Next, we use the registration tools in the cloud-based registration to shift and rotate the two groups of scans so that they match up with each other. This process caused a tiny error of 0.009 meters in the Grinnell Natural Area point clouds (Figure 3).

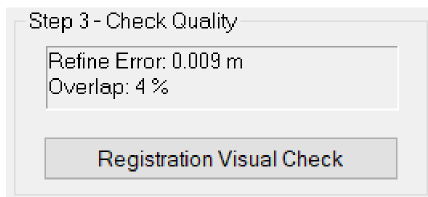

Figure 3. A 0.009 meter error was accumulated from adjusting a leveling issue in the Grinnell Natural Area point cloud during data registration.

Georeferencing the point clouds

The next task in the data processing of our terrestrial LiDAR scans was to georeference the Grinnell Natural Area point cloud to the control points located in the scans. By georeferencing the point-cloud, it can be compared with other point-clouds and maps such as campus maps and aerial LiDAR collected of the UC Berkeley campus. We only georeferenced the Grinnell Natural Area and not the Goodspeed Natural Area point-cloud because we did not have the minimum 3 control points in our Goodspeed point-cloud.

Because the scans produced by the Trimble TX6 scanner were in meters, we georeferenced our Grinnell point-cloud in meters. To do this georeferencing, we wanted our coordinate system to be in NAD 83 UTM Zone 10 North. We had three campus control points scanned into the Grinnell point-cloud, UCB 1621 (at Oxford Street), UCB 1623 (at Frank Schlessinger Way), and UCB 1631 (outside Haas Pavilion). The specific coordinates of these campus control points were found in the UC Berkeley campus wide control point report (BKF Engineers 2017). However, in the report, these campus control points were in the NAD 83 (2011) State Plane CA Zone III US Feet coordinate system. Therefore, we had to convert these 3 control points to NAD 83 UTM Zone 10 North coordinates. We converted the points by creating an Excel file with the campus control points in its original State Plane coordinates, then importing this file into ArcGIS. In ArcGIS, we used the Project tool (Figure 4) to convert the points from State Plane to UTM. This converted the Northing and Easting values in State Plane coordinates (Figure 5) to X and Y values for UTM. For the Z coordinate in UTM, we used the Elevation of the control point, but because we had spheres on top of these control points, we added 0.374 feet (radius of the sphere) so that we would get to the center of the sphere as the control point. These conversions only converted the coordinate system but not the units of measure, so all the new UTM coordinates (X, Y, Elevation) were multiplied by a factor of 0.304801 (conversion factor of U.S. feet to meters) to get the UTM coordinates in meters (Figure 6). After acquiring the UTM coordinates for the campus control points, we went back into the Trimble Realworks software and inputted the UTM coordinates into the georeferencing tool with the X coordinates, the Y coordinates, and the Z (elevation) coordinates for each campus control point. The tool showed that there was an average error of about 11 cm (Figure 7).

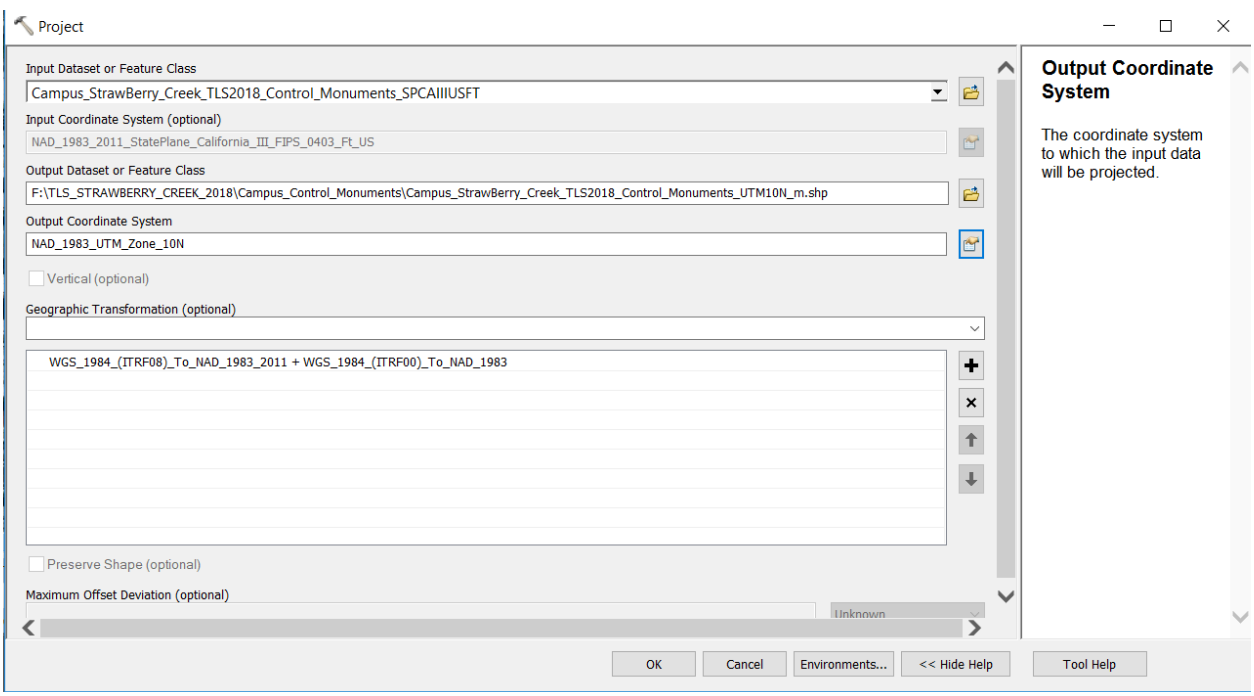

Figure 4. The Project tool in ArcGIS.

ID	N	E	El
UCB1621	2144109	6051991	201.38
UCB1623	2144306	6052696	229.44
UCB1631	2144065	6053136	243.21
UCB1633	2144326	6054518	309.69

Figure 5. The Campus Control Points coordinates in State Plane (N = Northing, E = Easting, El = Elevation).

FID	ID	sphereID	N	E	El	POINT_X	POINT_Y	POINT_Z	POINT_M	EL3	El3m	area	
0	UCB1621	110	2144108.89	6051990.89	201.38	564573.0155	4191661.1	201.38	1	201.754	61.49474	Grinnell	
1	UCB1623	10	2144305.77	6052696.1	229.44	564786.2233	4191726.815	229.44	1	229.814	70.04745	Grinnell	
2	UCB1631	173	2144065.2	6053136.34	243.21	564922.2829	4191657.122	243.21	1	243.584	74.24455	Grinnell	
3	UCB1633		2144326.3	6054517.59	309.69	565340.894	4191747.906	309.69	1	310.064	94.5077	Goodspeed	
													0.304801

Sheet1

Figure 6. The Converted State Plane Coordinates to UTM coordinates (in red) with the U.S. Survey feet to meters conversion of 0.304801 (bottom right).

Name1	Name2	Error
173	UCB 1631	0.117 m
Target1...	UCB 1623	0.082 m
110	UCB 1621	0.130 m

Average Error: 0.110 m

Display Errors

Figure 7. The amount of error accumulated from each control point (UCB 1631, UCB 1623, UCB 1621) and the average error added from georeferencing the Grinnell Natural Area.

We then applied all the points in the Grinnell point-cloud to be projected into the target UTM values. This operation transformed all the points in each of the 92 individual scans from the project coordinate system, which was in meters, into the global coordinate system (NAD83 UTM Zone 10N).

After we georeferenced the Grinnell point-cloud, we exported each individual scan as .las files (version 1.4), which is a type of LiDAR data storage file, so that we could analyze them in LiDAR software other than Trimble Realworks. The Goodspeed point-cloud was also exported as .las files (version 1.4).

Next, two point-based registration reports were downloaded from Trimble Realworks, one for the Grinnell point cloud and one for the Goodspeed point cloud. These two registration reports showed the overlap of points from other scans at each scan station. More specifically, the registration report showed the amount cloud-to-cloud error, the percentage of coincident points, and the percent confidence of this information between one scan station and other scans (Figure 8). The overall cloud-to-cloud error in the Grinnell Natural Area is 0.013 meters while the overall cloud-to-cloud error in the Goodspeed Natural Area was 0.011 meters. The two reports can be found on the hard drive passed on to Berkeley EH&S.

SC 001_Station 056_Scan 01 - 43 Station(s) with Points in Common -

Object Name	Cloud-to-Cloud Error	Coincident Points (%)	Confidence (%)
SC 001_Station 057_Scan 01	0.002 m	41%	100%
SC 001_Station 058_Scan 01	0.003 m	36%	100%
SC 001_Station 059_Scan 01	0.008 m	10%	100%
SC 001_Station 060_Scan 01	0.024 m	5%	100%
SC 001_Station 061_Scan 01	0.032 m	4%	18%
SC 001_Station 062_Scan 01	0.025 m	6%	100%
SC 001_Station 063_Scan 01	0.031 m	3%	16%
SC 001_Station 064_Scan 01	0.047 m	2%	10%
SC 001_Station 065_Scan 01	0.068 m	1%	4%
SC 001_Station 066_Scan 01	0.052 m	1%	6%
SC 001_Station 067_Scan 01	0.060 m	1%	3%
SC 001_Station 068_Scan 01	0.065 m	0%	2%
SC 001_Station 069_Scan 01	0.058 m	1%	5%
SC 001_Station 070_Scan 01	0.051 m	3%	13%
SC 001_Station 071_Scan 01	0.055 m	0%	2%
SC 001_Station 072_Scan 01	0.064 m	0%	2%
SC 001_Station 073_Scan 01	0.063 m	0%	1%
SC 001_Station 074_Scan 01	0.054 m	1%	4%

Figure 8. A view of the point-based registration report of the Grinnell Natural Area point-cloud showing the overlap of points from other scans to scan station 56.

Creation of Ground Points Only Point-Clouds

After scanning, the objective was to create two ground point models, one for the Grinnell Natural Area and one for the Goodspeed Natural Area to understand the geomorphology of the stream channel and banks. To do this, we used software called MapTek I-site Studio (Version 6.1).

First, we started a MapTek project for the Grinnell Natural Area and imported the .las files of the Grinnell Natural Area scans. While importing the scans, we had to option to define the coordinate system that we wanted to work in. Our coordinate system was in NAD83 UTM Zone 10N, so we input the ESPG (European Petroleum Survey Group) code for this coordinate system, 26910 (Figure 9). This allowed our .las file to stay georeferenced throughout our work in MapTek.

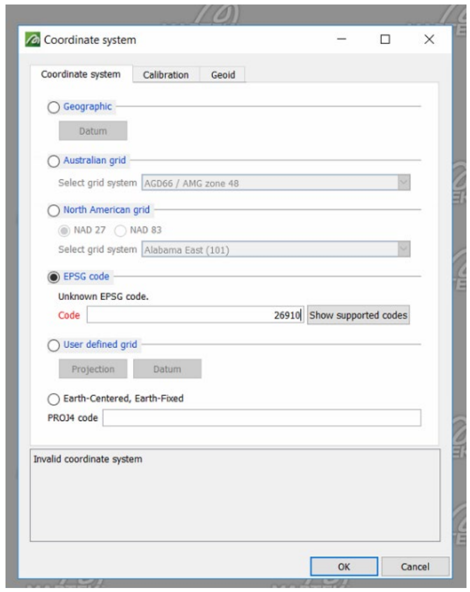

Figure 9. EPSG code 26910 input while importing scans into the project.

After importing the scans into MapTek I-site Studio, we wanted to subset our data points, so that it would become quicker for the software to analyze. We did this by using the "Minimum Separation Filter" tool (Figure 10) to separate points to a minimum spacing of 0.25 meters. The "apply filter to selection as a whole" box was left unchecked because we wanted each scan to have a 0.25 spacing and not the entire multi-scan project point-cloud.

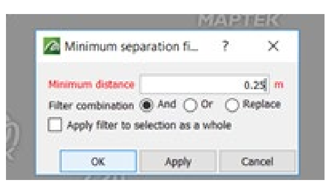

Figure 10. A minimum separation tool of 0.25 meters and its parameters.

Next, we used the "Topography Filter" tool (under Filter tab) and applied it to each scan. We did this one scan at a time because we did not want the software to crash from having to look through an immense amount of data points. Using the topography tool, we filtered the "lower points" out of each .las scan file using a 0.030 meter by 0.030 meter search cell (Figure 11). The resulting ground points were then exported into a single text .gb file. Then file was then imported into MapTek and assigned to the NAD 83 UTM Zone 10N reference system. Next, this .gb file was exported as a .las file, reimported back into MapTek, and assigned to the NAD 83 UTM Zone 10N reference system for further processing. Completing these steps allow the data to become easier to work with because all the individual scans were combined into a single .las file. The data points in this file were then colored based on elevation using the "Spectrum Height" tool under the Color tab (Figure 12).

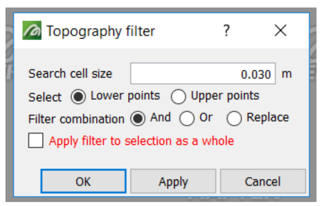

Figure 11. The topography filter of 0.030 meters and its parameters.

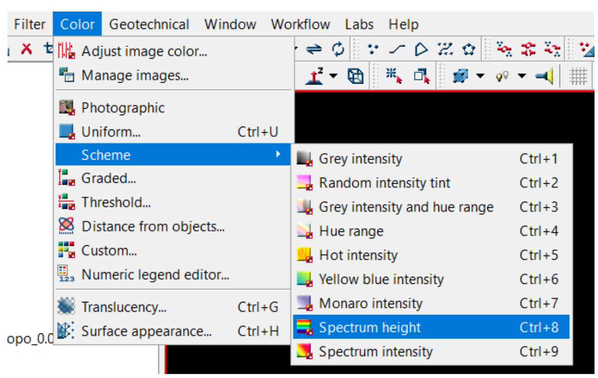

Figure 12. Location of the Spectrum Height tool in Maptek I-site Studio.

With the new single .las file we ran the "Minimum Separation" tool again with a minimum spacing of 0.25 meters, and then ran a "Topography Filter" with a search cell size of 1.50 meters. This operation deleted most of the above surface points in the file. For the best ground point model, we needed to try and delete the rest of the above surface points as well. Therefore, our next step was to manually select and delete points that were above the surface level. I used the "Select vertices" tool (Figure 13) to manually select points and the "Delete the selection" tool (Figure 14) to manually delete these selected points.

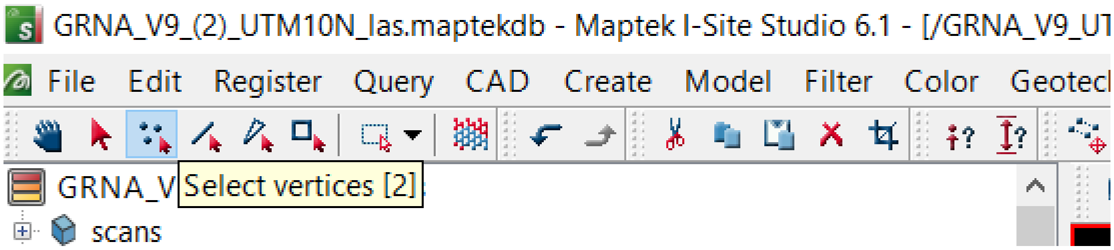

Figure 13. Location of the Select the vertices tool in Maptek I-site Studio.

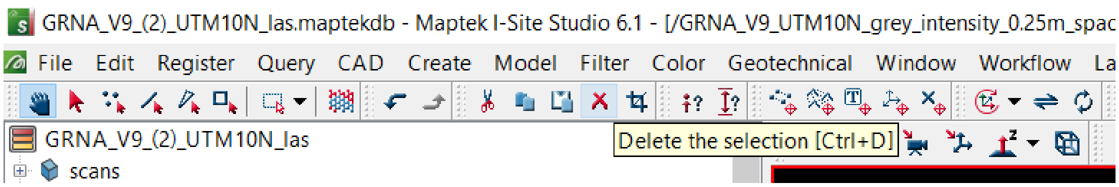

Figure 14. Location of the Delete the selection tool in Maptek I-site Studio.

After deleting as many ground points as I can, I went ahead and created a Triangular Irregular Network (TIN) by using the "Topography Triangulation" tool under the Model tab (Figure 15a). The "maximum boundary length" was set to 8.0 meters (Figure 15b).

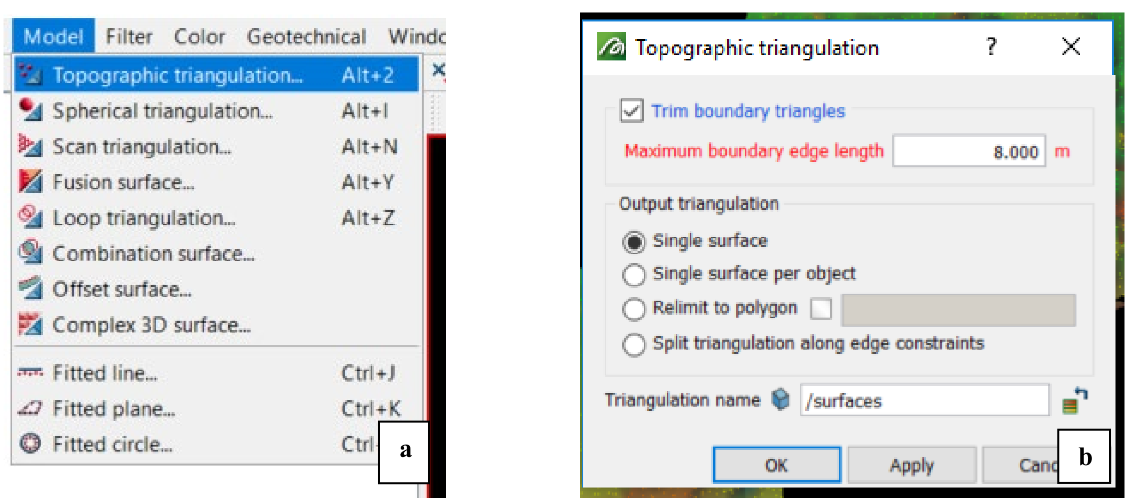

Figure 15. a) Location of the Topography triangulation tool in Maptek I-Site Studio. b) A Topography triangulation with a maximum boundary length of 8.0 meters and its parameters.

This operation created a ground surface model, however there were spikes in the model. Using the "Despike" tool under the Edit tab, and then the "Fill Holes" tool (also under the Edit Tab) (Figure 16), we were able to remove some of the spikes but many still remained. So next, we went back to the .las file where we were manually deleting above surface points and deleted more of these above surface points. Then we remade our TIN using the same parameters as before and ran the "Despike" and Fill Holes" tools again.

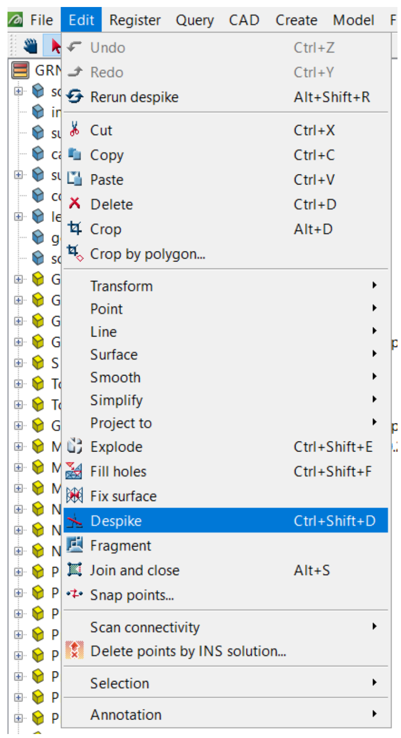

Figure 16. The location of the Despike tool in Maptek I-Site Studio.

This despiking process gave us a better model with less spikes but the detail of the TIN was poor. So next, we used the "Proximity Filter" (under Filter tab) to get closer to the actual ground points. This was done on the manually refined .las file with the TIN we created from it as the base object. The "Proximity Filter" was set to 0.200 meters and the "keep points close to base objects" box was checked (Figure 17).

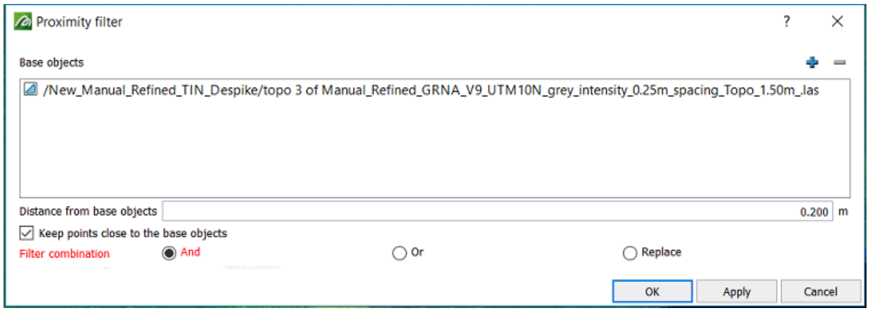

Figure 17. A proximity filter of 0.200 meters and its parameters.

The proximity filter will filter out points in our .las file that are not within 0.200 meters of the previous TIN we created. Next, we ran the "Topography Filter" tool with a search cell size of 0.800 meters keeping the "Lower points" and using the filter combination of "And". This topography filter divided the scan into horizontal grid cells of 0.800 meters and only kept the lowest points in the grids. Next, we created a TIN using the "Topography Triangulation" tool with the lightweight .las file scan that had went through the proximity and the topography filters. The new TIN was good in detail but could still be better. So, we combine the proximity filter, the topography filter, and the TIN creation, and ran a couple iterations of this with decreasing parameters to get closer and closer to the true ground points (Table 1).

Table 1: Iterations and parameters for filters of the lightweight .las scans of the Grinnell Natural Area.

Grinnell Natural Area	Prox. Filter	Prox. Filter Parameters	Topo. Filter	Topo. Filter Parameters	TIN Creation	TIN Parameters
Iteration 1	0.10 m	1. Use TIN created with 0.20 m Prox. Filter as Base Object 2. "yes" Keep points close to base object 3. Filter Combo: And	Search cell size: 0.6 m	1. Select: Lower Points 2. Filter Combo: And	"yes" trim boundary triangles Max. boundary edge length: 4.0 m	Output triangulation: single surface

Iteration 2	0.05 m	1. Use TIN created with 0.10 m Prox. Filter as Base Object 2. Keep points close to base object 3. Filter Combo: And	Search cell size: 0.4 m	1. Select: Lower Points 2. Filter Combo: And	"yes" trim boundary triangles Max. boundary edge length: 2.0 m	Output triangulation: single surface

After running these two iterations on the lightweight .las scan, the TIN looked much better in detail but to get the best detailed ground point TIN, we need to run our iterations on the full single individual .las scans. So next, we ran multiple iterations of the proximity filter, the topography filter, and the TIN creation on these full scans, with decreasing the parameter lengths on the filters each time so that we can get to the true and most detailed ground points. Below are the iterations and the parameters that I set on the filters for the full individual scans of the Grinnell Natural Area (Table 2).

Table 2. Iterations and parameters for filters of the full individual scans of the Grinnell Natural Area.

Grinnell Natural Area	Prox. Filter	Prox. Filter Parameters	Topo. Filter	Topo. Filter Parameters	TIN Creation	TIN Parameters
Iteration 1	0.05 m	1. Use TIN created with 0.05 m Prox. Filter from the Lightweight .las file as Base Object 2. "yes" Keep points close to base object 3. Filter Combo: And	Search cell size: 0.4 m	1. Select: Lower Points 2. Filter Combo: And 3. "No" to Apply filter to selection as a whole	"yes" trim boundary triangles Max. boundary edge length: 2.0 m	Output triangulation: single surface

Iteration 2	0.025 m	1. Use TIN created with 0.05 m Prox. Filter from Iteration 1 above as Base Object 2. “yes” Keep points close to base object 3. Filter Combo: And	Search cell size: 0.2 m	1. Select: Lower Points 2. Filter Combo: And 3. “No” to Apply filter to selection as a whole	“yes” trim boundary triangles Max. boundary edge length: 2.0 m	Output triangulation: single surface
Iteration 3	0.010 m	1. Use TIN created with 0.025 m Prox. Filter from Iteration 2 above as Base Object 2. “yes” Keep points close to base object 3. Filter Combo: And	Search cell size: 0.1 m	1. Select: Lower Points 2. Filter Combo: And 3. “No” to Apply filter to selection as a whole	“yes” trim boundary triangles Max. boundary edge length: 2.0 m	Output triangulation: single surface

Iteration 3 was the best and most detailed ground point model that was created using the full individual .las scans. The TIN created in Iteration 3 was exported as an .obj file onto the hard drive. The ground points from the full individual .las scans were exported as a single scan text file. Next, this single scan text file was reloaded into MapTek, and then it was exported as a single .las file onto the hard drive.

For the Goodspeed Natural Area, a similar method was employed. To begin, we created a MapTek project for the Goodspeed Natural Area and we imported the Goodspeed Natural Area .las scans. Next, we colored the scans by “Spectrum height” and also by “Grey intensity”. On the grey intensity scans, we ran the 0.25m “Minimum Separation” tool with the “apply filter to selection as a whole” box was left unchecked. Then we ran a “Topography Filter” with a search cell size of 0.030 meters on it.

Following this operation, we combined the full set of scans into a single .las file by exporting the grey intensity scans as a “single text file” after it has gone through the “minimum separation" tool and the "topography filter" tool. This "single text file" was then imported back into MapTek and then using this "single text file", we were able to export it as a single ".las" file. The single .las file was then imported back into MapTek. We colored this new .las file by "Spectrum Height" and then ran a "Topography Filter" with a 1.5-meter search cell size. This search deleted much of the above surface points but we wanted to get closer so we began to manually delete above surface points that were still present using the "Select vertices" tool and the "Delete the selection" tool. Then we ran the "Topographic triangulation" tool under the Model tab with a maximum boundary edge length of 8.0 meters to create a TIN surface. In this TIN, there were still many spikes present so we used the "Despike" tool under the Edit tab and then the "Fill Holes" tool (also under the Edit tab) to delete some of these spikes.

After these steps, we began to run the iterations of the proximity filter, topography filter, and the TIN creation in the Goodspeed Natural Area with the following parameters (Table 3).

Table 3: Iterations and parameters for filters of the Goodspeed Natural Area scans.

Goodspeed Natural Area	Prox. Filter	Prox. Filter Parameters	Topo. Filter	Topo. Filter Parameters	TIN Creation	TIN Parameters
Iteration 1	0.20 m	1. Use TIN created from the manually refined .las file as Base Object 2. "yes" Keep points close to Base Object 3. Filter Combo: And	Search cell size: 0.8 m	1. Select: Lower Points 2. Filter Combo: And	"yes" trim boundary triangles Max. boundary edge length: 8.0 m	Output triangulation: single surface
Iteration 2	0.10 m	1. Use TIN created from 0.20 m Prox. Filter in Iteration 1	Search cell size: 0.4 m	1. Select: Lower Points 2. Filter Combo: And	"yes" trim boundary triangles	Output triangulation: single surface

		above as Base Object 2. "yes" Keep points close to base object 3. Filter Combo: And			Max. boundary edge length: 4.0 m	
Iteration 3	0.05 m	1. Use TIN created from 0.10 m Prox. Filter in Iteration 2 above as Base Object 2. "yes" Keep points close to base object 3. Filter Combo: And	Search cell size: 0.4 m	1. Select: Lower Points 2. Filter Combo: And	"yes" trim boundary triangles Max. boundary edge length: 4.0 m	Output triangulation: single surface
Iteration 4	0.05 m	1. Use TIN created from 0.05 m Prox. Filter in Iteration 3 above as Base Object 2. "yes" Keep points close to base object 3. Filter Combo: And	Search cell size: 0.4 m	1. Select: Lower Points 2. Filter Combo: And 3. "No" to Apply filter to selection as a whole	"yes" trim boundary triangles Max. boundary edge length: 4.0 m	Output triangulation: single surface
Iteration 5	0.025 m	1. Use TIN created from 0.05 m Prox.	Search cell size: 0.2 m	1. Select: Lower Points	"yes" trim boundary triangles	Output triangulation: single surface

		Filter in Iteration 4 above as Base Object 2. "yes" Keep points close to base object 3. Filter Combo: And		2. Filter Combo: And 3. "No" to Apply filter to selection as a whole	Max. boundary edge length: 4.0 m	
Iteration 6	0.010 m	1. Use TIN created from 0.025 m Prox. Filter in Iteration 5 above as Base Object 2. "yes" Keep points close to base object 3. Filter Combo: And	Search cell size: 0.1 m	1. Select: Lower Points 2. Filter Combo: And 3. "No" to Apply filter to selection as a whole	"yes" trim boundary triangles Max. boundary edge length: 3.0 m	Output triangulation: single surface
*** Iterations 1-3 were completed using the Lightweight single .las file to run the proximity filter, topography filter, and TIN creation.** **** Iterations 4-6 were completed using the Full individual .las scans to run the proximity filter, topography filter, and TIN creation.**						

The TIN created in Iteration 6 was the best and most detailed ground point model completed using the full individual .las scans. This TIN was exported as an .obj file onto the hard drive. The ground points from the full individual .las scans were exported as a single scan text file. Next, this single scan text file was reloaded into MapTek, and then it was exported as a single .las file onto the hard drive.

RESULTS

The terrestrial LiDAR scanning (TLS) took 4 straight 12-hour days to complete with 3-5 people working on it at a time. In the Grinnell Natural Area, 92 total scans were taken. Of these 92 scans, 79 were scans of the Strawberry Creek channel and 13 scans were necessary to add in control points to the point-cloud (Figure 18). In the Goodspeed Natural Area, 53 total scans were taken. Of these 53 scans, 50 were scans of the Strawberry Creek channel and 3 were control point scans (Figure 19).

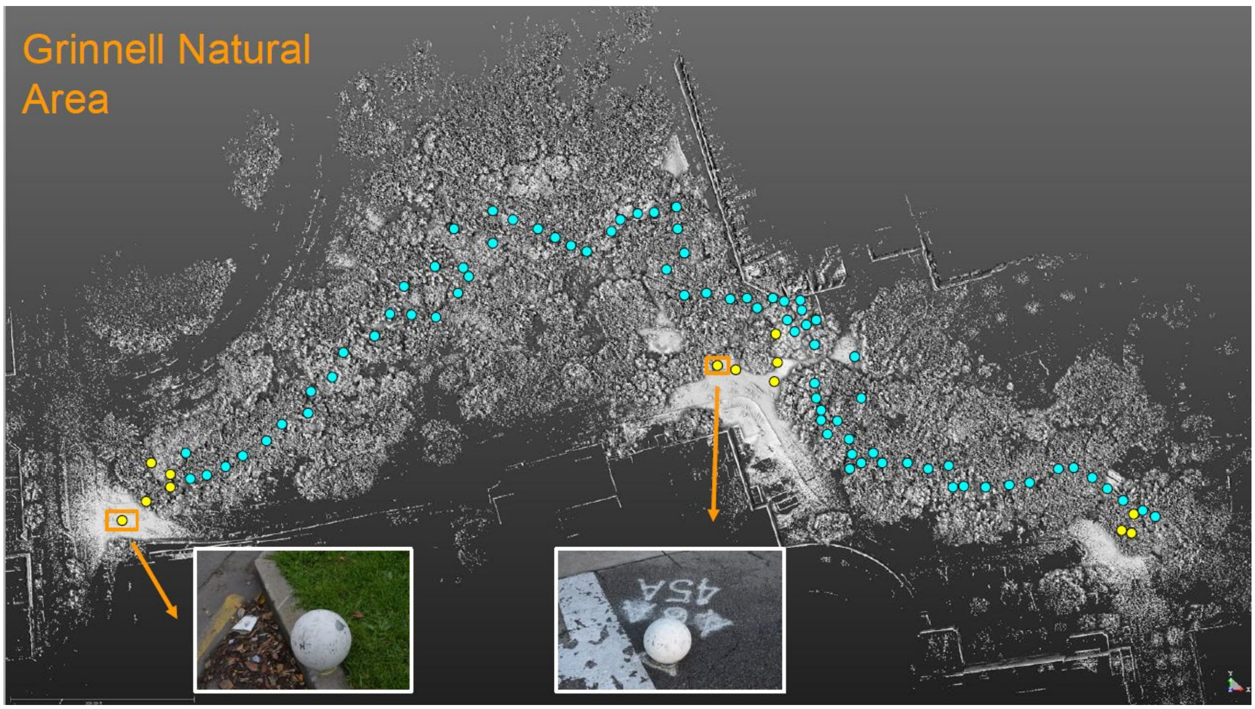

Figure 18. A map of all the terrestrial LiDAR scans taken in the Grinnell Natural Area. The blue dots are the scans of taken of Strawberry Creek while the yellow dots are the scans taken of the control points.

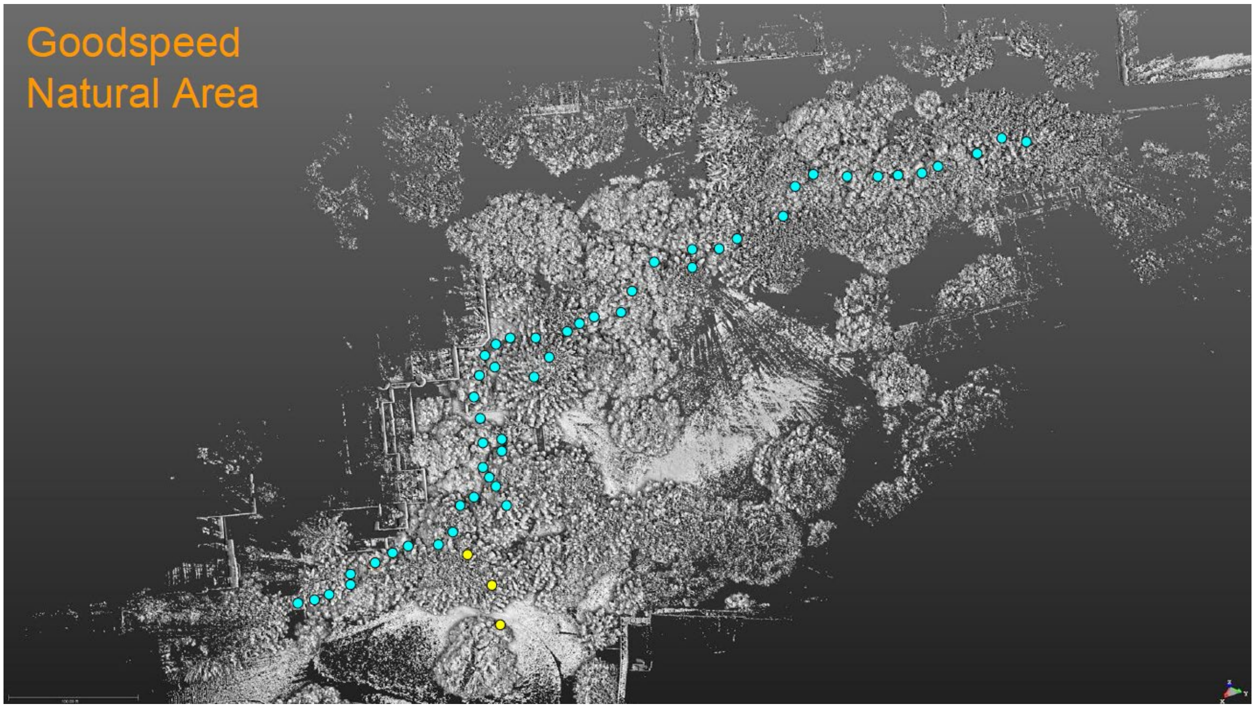

Figure 19. A map of all the terrestrial LiDAR scans taken in the Goodspeed Natural Area. The blue dots are the scans of taken of Strawberry Creek while the yellow dots are the scans taken of the control points.

At each scan station .JPG images were taken in color. In the Grinnell Natural Area, the images were taken when the scanner was facing one direction (Figure 20a). In the Goodspeed Natural Area, 360-degree image was taken around the scanner (Figure 20b) along with an intensity .JPG image (Figure 20c).

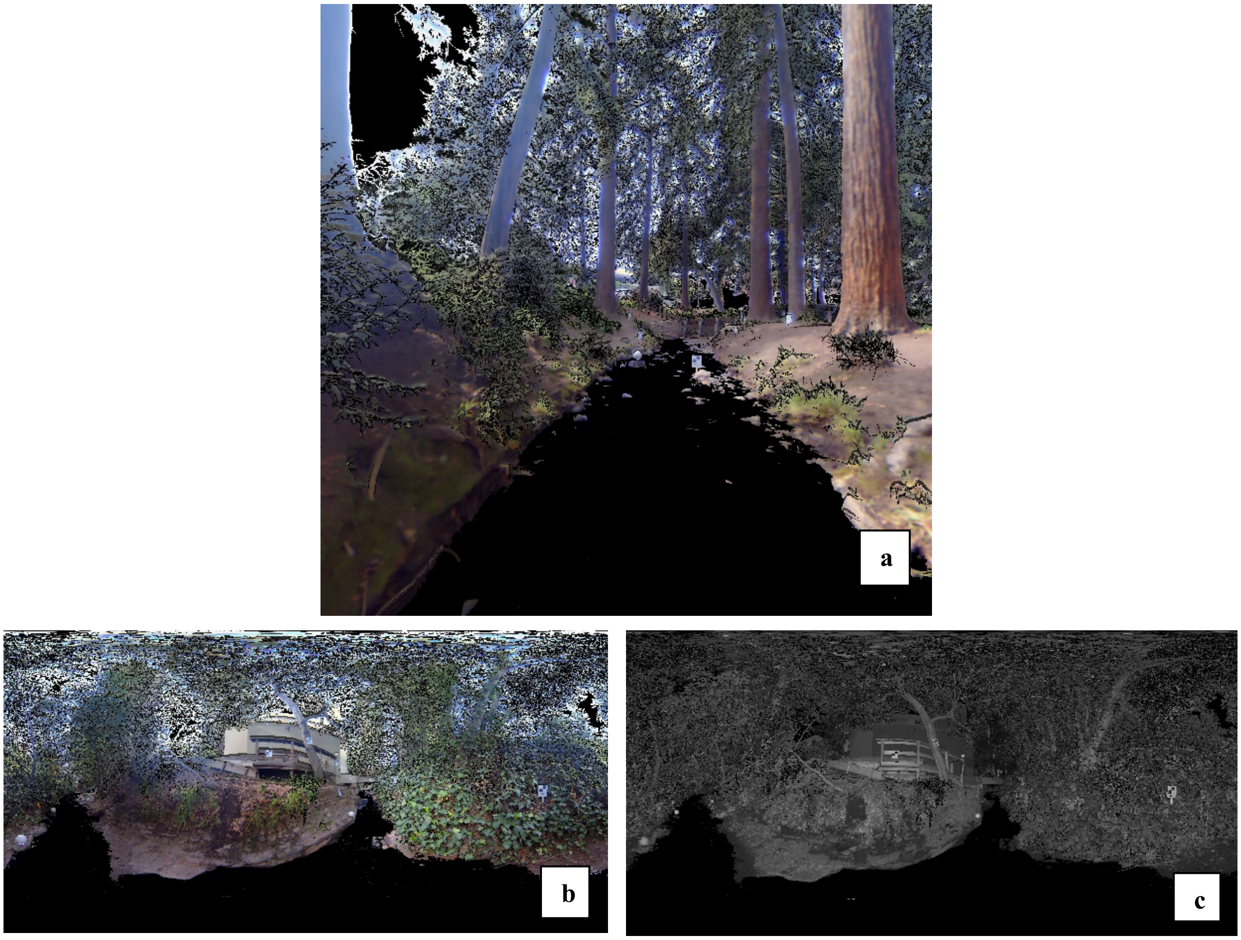

Figure 20. a) A color image taken by Trimble TX6 in the Grinnell Natural Area. b) A color image taken by Trimble TX6 in the Goodspeed Natural Area. c) An intensity image taken by Trimble TX6 in the Goodspeed Natural Area.

After building the two main point clouds for each of the natural areas, we wanted to find the ground points in the two natural areas of Strawberry Creek. Using the tools in MapTek, we built one ground point-model for the Grinnell Natural Area and one for the Goodspeed Natural Area. This required a number of steps to decrease the number of points in the dataset and refine the data until we had only the ground points in each point-cloud.

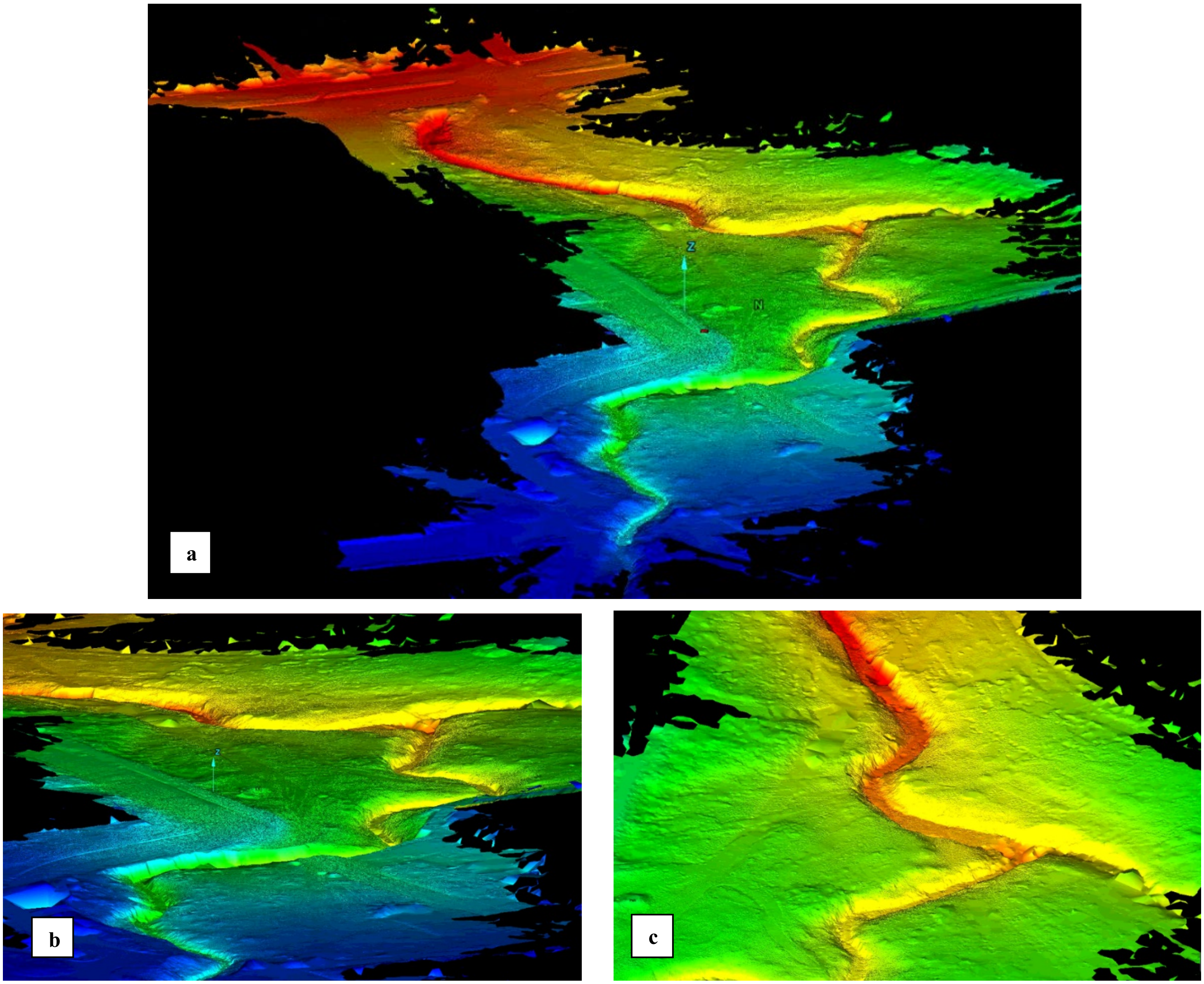

Figure 21. A Triangular Irregular Network (TIN) created for the Grinnell Natural Area. a) A view of the entire ground-point model for the Grinnell Natural Area. b) A view of the Grinnell TIN looking diagonally. c) A close-up view of the Strawberry Creek stream channel from the Grinnell Natural Area TIN.

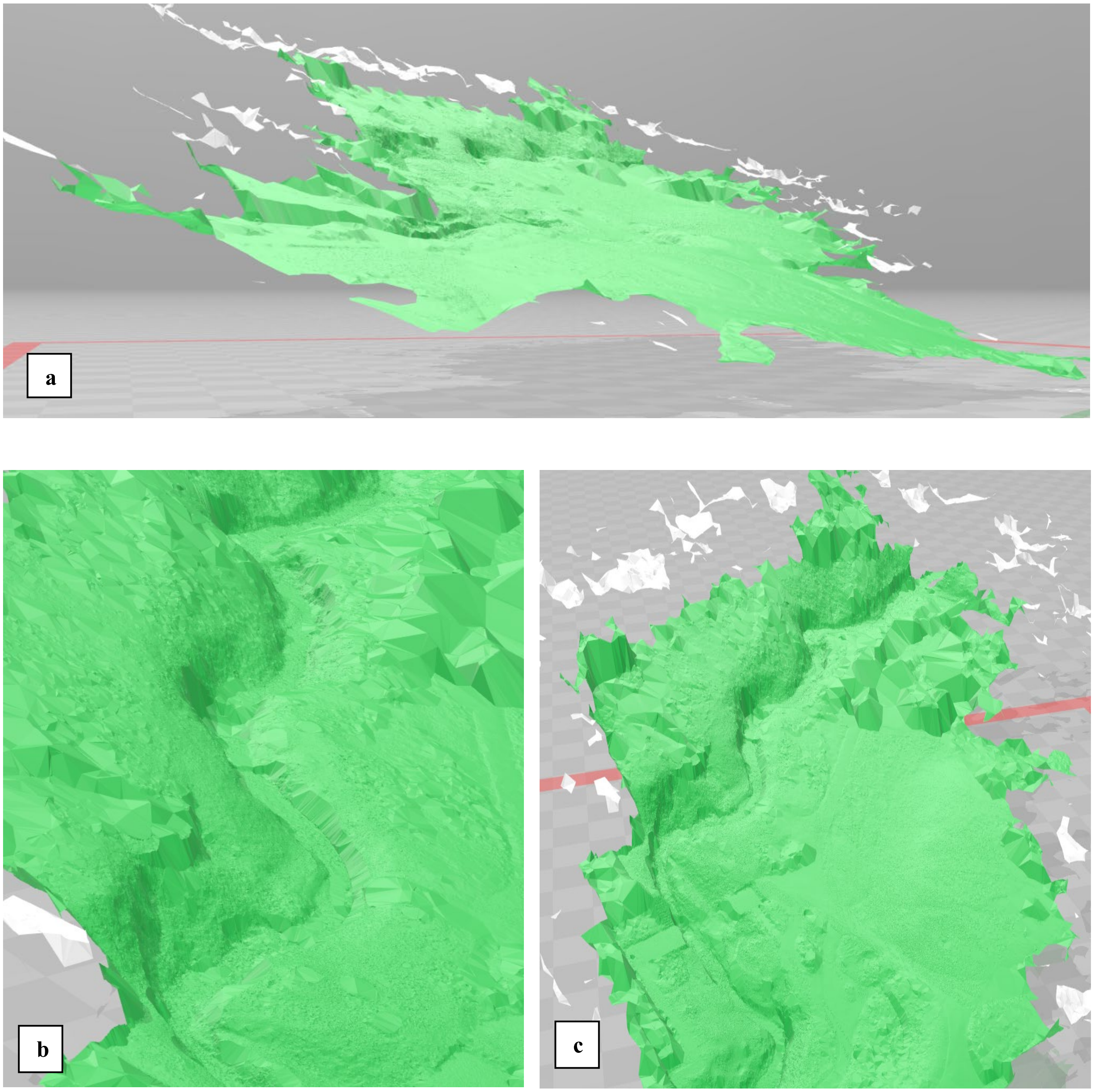

Figure 22. A Triangular Irregular Network (TIN) created for the Goodspeed Natural Area. a) A view of the entire ground-point model for the Grinnell Natural Area. b) A close-up view of the Strawberry Creek stream channel from Goodspeed Natural Area TIN. c) A top down view of the Goodspeed TIN.

DISCUSSION

Through the gathering of terrestrial LiDAR data in Strawberry Creek, we were able to gather data under the dense vegetation that the aerial LiDAR could not. However, in the process of data collection in the field, errors were made that affected the accuracy in our point-clouds. We were able to reconcile the LiDAR data and minimize the error. Additionally, the data helped create ground point models for the 2 natural areas to help understand the geomorphology of the stream and can become a reference for how future terrestrial LiDAR data can be collected in stream riparian zones.

Accuracy in our terrestrial LiDAR scans and point-clouds

The terrestrial LiDAR scans and point-clouds of Strawberry Creek in the Grinnell Natural Area and the Goodspeed Natural Area were completed to the best of our ability; however, we encountered a number of challenges that affected the precision of our model. One key issue was the difficulty in georeferencing our LiDAR scans to the UC Berkeley campus control points in the two natural areas. Georeferencing was a problem because the terrestrial LiDAR scans were taken in metric meters while the campus control points had a coordinate system in U.S. Survey feet. To correct for the difference in coordinate system and to reconcile the LiDAR data and the campus control points into the same coordinate system of meters, we had to convert the campus control point coordinate system of State Plane U.S. Survey feet to UTM meters. This created a slight error because the conversion coefficient between the two coordinate systems was not exact. As a result, after we georeferenced the Grinnell Natural Area in UTM, the average error across the Grinnell point-cloud was approximately 11 cm. This number could have been smaller if our LiDAR scans were taken in U.S. Survey feet so that it would match the coordinate system of the campus control points.

For the Goodspeed Natural Area, the LiDAR scans were also taken in metric meters. However, we were unable to georeference the point-cloud at all because we were only able to gather 1 control point for the Goodspeed Natural Area. In order to georeferenced a point-cloud in Trimble Realworks, there needs to be at least 3 control points present within the point-cloud. A solution to this problem would be to take more scans in the Goodspeed Natural Area with a terrestrial LiDAR scanner and make sure that 2 or more control points are in these additional scans. Alternatively, a Total Station (e.g., survey equipment) could be used to identify the coordinates of an edge of a building present in the Goodspeed point-cloud. This total station would be able to gather the specific coordinates of the edge in the UTM coordinate system. The edge would then become a control point and its UTM coordinates could be input into the Goodspeed point-cloud for it to be georeferenced. At least 2 more UC Berkeley coordinate system points are needed for the Goodspeed Natural Area.

Because our LiDAR scans were not collected in U.S. Survey feet units and not enough control points were gathered for the Goodspeed Natural Area, georeferencing in this study was incredibly difficult and took an immense amount of time. The error in our georeferenced Grinnell point-cloud was 11 cm when it should have been only millimeters of error. This means that the absolute accuracy in this terrestrial LiDAR scanning study was decreased. Absolute accuracy tells us how true the data in our point-clouds are compared to the geographical UTM mapping coordinates. Point-clouds with great absolute accuracy are extremely useful when comparing to other maps and point-clouds.

Although the absolute accuracy to the coordinate system in the study was poor, the relative accuracy was quite high for both the point-clouds in our study. For the Grinnell Natural Area, we had a cloud to cloud error of 13-millimeters and for the Goodspeed Natural Area, we had a cloud to cloud error of 11-millimeters. This means that there was a 13-millimeter difference between any 2 objects in the Grinnell point-cloud and the same 2 objects in the field. In the Goodspeed point-cloud, there is an 11-millimeter difference between any 2 objects in that point-cloud and the same 2 objects in the field. Point-clouds with a high relative accuracy, like our study, allows us to make precise measurements in these areas of our point-clouds.

Benefits and Challenges of Working with TLS

Challenges of Working with TLS

In conducting terrestrial LiDAR research for this study, there were many challenges related to logistics and data processing. One of these challenges involved conducting terrestrial LiDAR scans in the field. My team and I felt that we could have completed the fieldwork more efficiently if we had more manpower to help with the scanning. In our project we usually had 2-3 people working on scanning Strawberry Creek at a time and sometimes we even had up to 5 people helping with the setup of spheres and targets and to conduct the LiDAR scans. To increase the efficiency of terrestrial LiDAR scanning, jobs should be assigned so that each person has a specific role. In our study, at times one person moved the LiDAR scanner at one moment and the next moment this same person would also be trying to set up targets and spheres on the banks. When one person tried to complete multiple tasks during and between the LiDAR scanning, time was lost and we were unable to maximize the number of scans we could have taken. Ideally, there would be 1-2 people focused on just setting up the targets and spheres and 1-2 focused on just moving the scanner between scan spots and then running the scanner to increase efficiency in completing the scans in the field.

In addition, we needed a person to monitor crowd control and answer questions while the rest of us ran the LiDAR scanner in the creek. This would have also increased the efficiency of the data collection in the field. For example, during one of our terrestrial LiDAR scans, a member of the public kicked over a sphere. Many people passing by were also curious about our project and would ask us questions about it and our scanner. This public outreach took some time away from the actual scanning time because we only had limited manpower and daylight to conduct the scans.

Another challenge that was encountered in the field during data collection was weather. During one of the days of scanning, we encountered a heavy downpour. Initially we decided to continue to scan through this downpour by holding an umbrella on top of the scanner. Doing this added a task to our data processing because we had to manually remove the umbrella from the point-clouds. In addition, during the downpour, the lenses on the scanner began to fog up, thereby producing fuzzy scans that could not be used. As a result, we had to stop scanning until the rain stopped, which limited the time we had to completed all the necessary scans at the Goodspeed Natural Area. This rain delay led us to only being able to capture 1 control point for this natural area.

Benefits of Working with TLS

Although there were challenges in working with terrestrial LiDAR, there were also immense benefits that we gained by conducting these scans. Terrestrial LiDAR scanning was able to increase the relative accuracy of our measurements, helping us make measurements down to the millimeter level. Due to human error already mentioned, the absolute accuracy in this study was poor, allowing approximately a 10-13 cm of error. Without human error, absolute accuracy could have also been accurate to the 2-millimeter level.

In addition, the 3D point-clouds built from the terrestrial LiDAR scans will be able to help derive measurements for areas along Strawberry Creek for subsequent research projects. These measurements include the tops of trees, characteristics of the water channels, characteristics of the stream banks, etc. However, because the surface of the water did not return a signal to the LiDAR scanner, the depth and channel morphology of the wetted channel does not yet contain data. This means that in scans and photographs, these areas appear black as a result of the missing data. To derive long profiles, cross-sections, and other data products from these scans, additional data will need to be acquired using a Total Station within the channel.

A major benefit of a LiDAR project is that all the files of the scans and the registered point-clouds will be available digitally if they need to be revisited. If the scans were collected correctly the first time, no additional time would be spent in the field collecting more data. The majority of the time spent on a LiDAR project should be in the lab conducting data processing and data analysis. To make another measurement, we would only need to go back to the LiDAR point-clouds to make the measurement instead of returning to the field to set up for more days of fieldwork had we used traditional measurement tools. This digital record should reduce future fieldwork expenses and potentially create additional projects that could use the same dataset to answer a different question. However, this dataset is limited because the ecology of an area may change over time so there is an expiration date on the LiDAR point-clouds collected, yet it also serves as a snapshot of conditions that can serve as baseline data for future comparisons to environmental change.

Further Studies

In subsequent research studies on Strawberry Creek, the data from the point-clouds constructed in this project can certainly help assist in answer questions about the stream. Some of these potential topics could include questions about management decisions along the stream. For example, how could this dataset help answer questions about erosion along the stream? Where are the areas with little vegetative cover and how big are they? Additional questions could explore how close the trees are to the stream and how much canopy cover it provides for the stream. There are also questions on the channel characteristics that can be explored. These channel characteristics could be visualized in the point-cloud constructed in this study to help answer questions on how to better manage flood control on the creek during the wet winter months.

Conclusion

Although terrestrial LiDAR scanning can be challenging both in terms of fieldwork procedures and data processing, the potential benefits could outweigh the challenges. Terrestrial LiDAR allowed us to create two point-clouds of two natural areas in Strawberry Creek with high relative accuracy and has helped us gather information that might not have been possible to collect otherwise. Using this technology, we were able to gather data underneath the thick vegetation that aerial LiDAR could not collect. This terrestrial LiDAR data will allow us to make various measurements to assist in future management decisions for Strawberry Creek.

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