LIDAR AND SRTM: A CASE STUDY OF THE NAVAL SURFACE WARFARE CENTER, DC

by

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A Thesis
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of
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The Requirements for the Degree
of
Master of Science
Geoinformatics and Geospatial Intelligence

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DEDICATION

This is dedicated to my loving wife Adriana, my two wonderful children Joseph and Isabella.

ACKNOWLEDGEMENTS

I would like to thank the many friends, relatives, and supporters who have made this happen.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

American Standard Code for Information Interchange	ASCII
Chesapeake and Ohio	C&O
Computer Aided Design	CAD
Continuously Operating Reference Station	CORS
Digital Elevation Model	DEM
Digital Line Graph	DLG
Digital Surface Model	DSM
Digital Terrain Elevation Dataset	DTED
Digital Terrain Model	DTM
District of Columbia	DC
Environmental Systems Research Institute	ESRI
European Petroleum Survey Group	EPSG
Federal Emergency Management Agency	FEMA
Fundamental Vertical Accuracy	FVA
Geographic Information System	GIS
Global Positioning System	GPS
Graphic User Interface	GUI
Improvised Explosive Device	IED
Inertial Measurement Unit	IMU
Inertial Navigation Systems	INS
Infrared	IR
Joint Photographic Experts Group	JPG
Keyhole Markup Language	KML
Laser file format	LAS
Laser file format ESRI decompressor	LASX
Laser file format zipped	LAZ
Light detection and ranging	LIDAR
Mean Sea Level	MSL
National Elevation Data	NED
National Geodetic Survey	NGS
North American Datum	NAD
North American Vertical Datum	NAVD
Portable Network Graphic	PNG
Real Time Kinematic	RTK
Root Mean Square Error	RMSE
Shuttle Radar Topographic Mission	SRTM

Three-dimensional 3D
Triangulated irregular network ....TIN
United States Geological Survey .... USGS
Universal Transverse Mercator ....UTM
Variable Length Record ....VLR
World Geodetic System ....WGS

ABSTRACT

LIDAR AND SRTM: A CASE STUDY OF THE NAVAL SURFACE WARFARE CENTER, DC

Gregg J. Heitkamp, M.S.

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Light detection and ranging (LIDAR) has been evolving for over forty years and has become a wide used technology that most people see or utilize almost daily. It was initially used as a ground based system to map particles in our atmosphere. This technology has spread into Archeology, Agriculture, Meteorology and Atmospheric Environment, Biology and Conservation, Law Enforcement, Autonomous driving, and the focus of this thesis is mapping.

The main focus of this thesis is the process of mapping areas with LIDAR data and comparing the accuracy with older elevation data; Shuttle Radar Topography Mission, SRTM. For processing data, we go through four separate phases depending on your data and desired final product. Initially, it is recommended to perform quality checks, data preparation, derivative production, and finally editing the LAS files before distribution. The first product was processing raw LIDAR data and covering it with

imagery for the Kameni Islands of the Santorini caldera in Greece. The main product was for the Naval Surface warfare Center outside of Washington DC along the Potomac River. I downloaded LIDAR data and cut an area of interest from Open Topography. I then downloaded imagery and SRTM data from United States Geological Survey, USGS, Earth Explorer for comparing the LIDAR data to Imagery and SRTM. Next, I was able to find survey control points in the region from the National Geodetic Survey, NGS, data explorer to compare the LIDAR data to the survey control points. We finally compared the final LIDAR data with SRTM data. SRTM data has larger point spacing and an accuracy of ~20 meter horizontal and ~10 meter vertical accuracy compared to the LIDAR data that is ~3 meter and between centimeter and decimeter vertical accuracy. There was also some data processing for terrestrial LIDAR survey for an area near Prescott, Arizona.

Introduction

This paper first explains what LIDAR is, how it is used, and the advancement of this technology towards better accuracy and efficiency of modern day mapping. First, the paper will explain what LIDAR is and how it has progressed to its current modern day technology. Then we will look at the different factors that make up LIDAR and how it factors in the final finished product. Finally, we will look at the products that are utilized and created to solve problems.

Problem

There are numerous elevation datasets available depending on the desired final product and location. LIDAR data is more accurate and denser than SRTM, DTED, etc. After finding the LIDAR data, depending on the data and final product, numerous different processes will need to be performed.

CHAPTER 1: INTRODUCTION

Section One: What is Lidar

To understand lidar, it is best to know where lidar evolved from. It is over forty years old and initially used to map particles in the atmosphere. This ground based lidar was fixed at a location that never moved with accurate coordinates. In the 1980's, Global Positioning System (GPS) opened lidar to a mobile platform. [9] With this mobile platform, airborne lidar was born. In the early 1990's, Inertial Measurement Unit (IMU) was improved and lidar data had the ability to have an accuracy of approximately a decimeter. [9] With Ground control points embedded in the processing, accuracy can vastly improve depending on the layout of the ground control points. With evolving technology and size reduction, lidar sensors are small enough to be used on vehicles and as a survey terrestrial unit. The accuracy has improved to have an accuracy of a centimeter on ground based lidar systems. [9]

Light detection and ranging, LIDAR, is becoming a very popular and accurate way of mapping the Earth. Lidar has become a well-established and proven method for collecting very dense and accurate elevation data across various landscapes, shallow water regions, and particular project sites. Lidar is an active sensor that sends out Laser beams or light pulses that measure the distance from the sensor to the targets. It can be used in mapping the earth's surface, determining the elevation of the surface or building three-dimensional (3D) models for representations of buildings or other natural or manmade features. Lidar sensors are mainly used from various aircraft; helicopters and airplanes to build elevation data. This technology is also used in terrestrial survey and mobile systems for building 3D models or areas that airborne lidar would not be able to measure.

There are several applications for Lidar technology; Archaeology, Meteorology and Atmospheric Environment, Geology, Physics and astronomy, Biology and conservation, Law enforcement, Vehicles, Imaging, and 3D mapping. Lidar has many capabilities in Archaeology which include mapping features underneath forest canopy or displaying small continuous features that may be indistinguishable on the ground. In Meteorology and Atmospheric Environment, lidar is used to study the atmospheric composition, structure, clouds, and aerosols. It can also be used to determine wind velocity and provide global measurements of vertical wind profiles. In Geology, lidar is typically used to detect faults and measure the uplift by doing change detection of the ground surface. Lidar is used in Physics and astronomy to measure the distance to reflectors on the moon. It also mapped Mars and detected snow in its atmosphere. It is also used to measure certain constituents of the middle and upper atmosphere. Biology and conservation use lidar to calculate canopy heights, biomass measurements of land plants, estimation of phytoplankton fluorescence on the surface layer of the ocean, and leaf area. Radar guns are lidar technology that the law enforcement personnel use to detect vehicle speeds. Vehicles use lidar for distance detection. The system monitors the distance between bumpers and nearby objects. Lidar is widely used for imaging, purposing, and creating 3D images of objects.

There are two main tracking systems used with the LIDAR sensor to know the exact position of the sensor; Global Positioning System (GPS) and Inertial Measurement Unit (IMU) or Inertial Navigation Systems (INS). GPS instruments use signals received from GPS satellites to acquire the position of the instrument and needs signals from at least four satellites for an accurate position. They also need direct radio contact with the satellites. IMU or INS is an electronic device that measures and reports velocity, orientation, and gravitational forces. It uses a combination of accelerometers and gyroscopes for the orientation of the sensor platform. This system is not as accurate as GPS, but can temporarily replace GPS if mapping inside of a tunnel or area that has no exposure to the GPS satellites. The INS or IMU will keep an accurate position for about one second. [9] Hence the GPS instrument gives an update every 30 seconds, to keep the sensor at a known position. [9] The systems rely on each other to keep an accurate location of the lidar sensor. The figure below is an example of how the systems relate to one another.

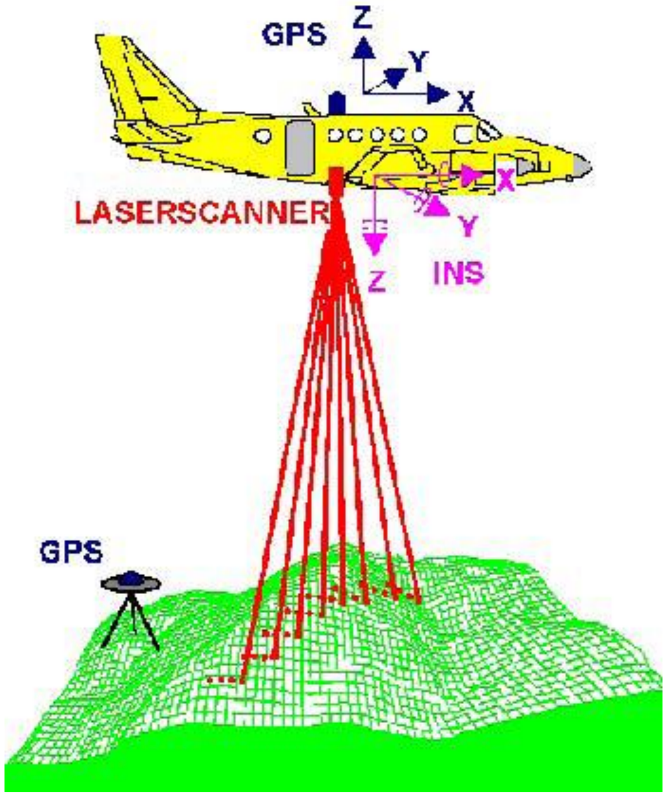


Figure 1: Basic Lidar Collection Schematic

The Lidar sensor can produce a rapid collection of points, more 200,000 per second. [15] Lidar light pulses are typically sent out at 532nm to 1550nm. [13] The wavelength depends on what type of data the user is trying to retrieve. The green light at 532nm is used for water depth detection up to 50 meters in clear water. [17] Airborne lidar is typically taken in near IR, 1024-1064nm. [16] Ground based or terrestrial lidar is commonly found at 1550nm. [14]

With each pulse, the sensor can receive up to five separate returns. Typically, the first return is the strongest. The other returns can have a lower level, which normally indicates vegetation interference, window interference on a building, or the surface layer of water. This allows the imagery to be able to map vegetation heights as well as ground elevation. With bathymetry, it would show the water depth using the difference between the first return of the water surface and the last return of the sea floor. The figure to the right shows a diagram of how there can be up to five returns and how it would look like on vegetation. [9]

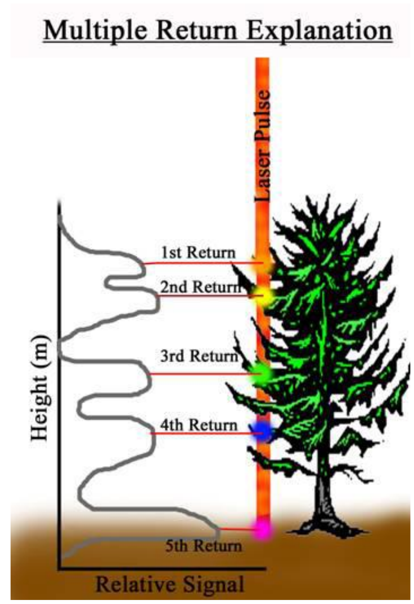


Figure 2: Multiple Return explanation

Timing and position are crucial for lidar calculations. Lidar distance is derived by the speed of light times the wavelength divided by two. GPS instruments are constantly being updated of the time and current position by the GPS satellites. The GPS instruments then update the IMU. With the GPS and IMU, the sensor knows the exact position of when it sent out the pulse and the returns. By taking the distance and position, the return can be calculated accurately. The system knows the wavelength distance and multiples it by the time to get the total distance between the sensor and satellite. With the known location of the sensor, the distance, and direction to the object then the coordinate of reflected position is configured.

Lidar relies on two sets of measurements to generate a cloud of points for features around the known location of the scanner. The first measurement is the direction of the Laser to the target. Depending on the scanner, the points may be evenly or unevenly distributed on the target. Most systems operate on an angular offset between successive measurements. Typically, the closer the target the higher point density. The second crucial measurement is the distance to the point. With the azimuth or direction and distance, the location of the target can be plotted correctly.

There are two approaches to measuring the distance of the lidar pulse returns; time-of-flight and phase-based. The time-of-flight sends a pulse, waits, and then measures the time of arrival of the return pulse or pulses. With the travel time a precise distance can be measured. Time-of-flight is only limited by the need of a return signal. High powered terrestrial systems can see out to kilometers or more as needed. It is limited by the system requirement not to harm persons in the target area and the gradual spread of the beam compared to the distance.

The phase-based lidar sends a continuous beam with known phases. The phases are shifted once it hits the target and this returned shifted signal is processed to derive the distance. This method is faster and more accurate than the time-of flight, but it has limitations in distances for terrestrial surveys.

One major problem with Lidar is its availability, because it does not function in cloud cover or in foggy conditions. The Lidar pulses will not be able to penetrate this type of atmospheric disturbance. Lidar cannot be used in heavy vegetation if the purpose is to acquire the elevation data of the ground. Most GPS instruments are set up to record a position every second. When using airborne Lidar, if the plane shifts suddenly because of wind or sudden atmospheric drop in pressure, the GPS will give the sensor the wrong reading during this split second. By using Lidar at 1550nm, it can penetrate through most of the natural haze. [17]

When conducting most lidar scans, a digital photo is taken. When processing the data, the real image photo can be draped on top of the lidar data. This gives a real life effect to the data. This is more commonly seen in terrestrial lidar surveys. An urban area is brought to life.

Section Two: Airborne Lidar

The first type of LIDAR sensor we will discuss is the airborne platform. A plane or helicopter will contain a sensor with a GPS and IMU instrument. The airborne device will fly a predestined path and take LIDAR readings. The readings will be registered with ground based GPS control points. The GPS instrument on the aircraft contains the exact position and timing of the aircraft and the ground based GPS instruments will align the LIDAR imagery to the correct post-processed location. For airborne imagery, higher frequencies are required due to eye safety of people on the ground. [17] The figure to the right shows a diagram of how an airborne system interacts with its relative parts. [11]

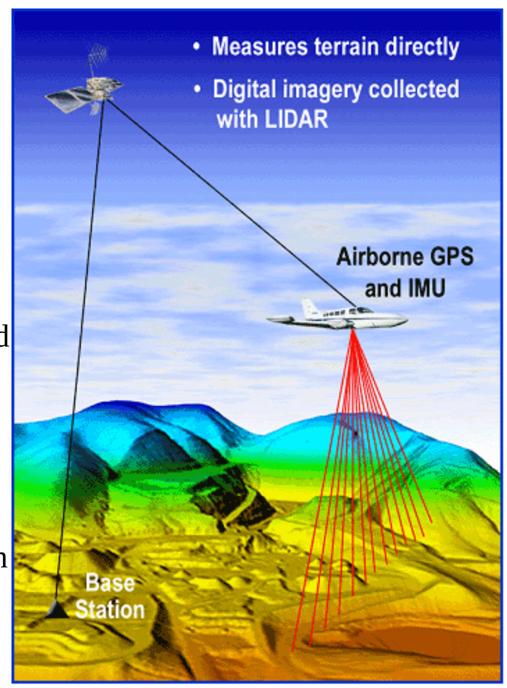


Figure 3: Airborne Lidar

Airborne imagery is the most popular type of lidar and has multiple uses. For the military, the buckeye system is widely used. It is a field expedient change detection system used to aid in the detection of improvised explosive devices (IED). It can operate at multiple altitudes depending on the desired image resolution and image swath. The system uses lidar technology to capture the elevation of the desired area; normally along roadways. By comparing data, it can detect surface elevation variances that indicate possible positions of IEDs as seen in the figure below [2]. This system has saved countless lives in Iraq and Afghanistan. [2]

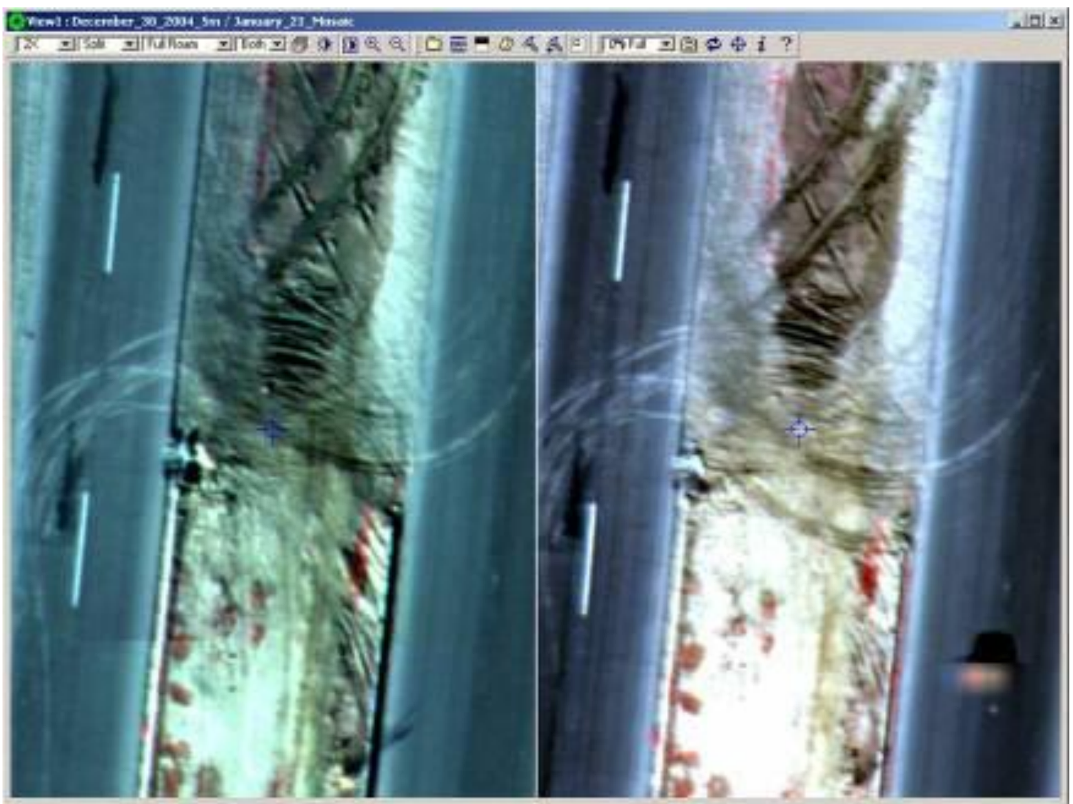


Figure 4: Change Detection using Buckeye

Forest and tree studies are another powerful use of lidar for the timber companies. By using the multiple returns, lidar computation can calculate tree spacing, canopy cover, and tree height. This tool aids the timber company on the volume of wood that can be extracted from a particular site. By knowing this information, the timber company does not need to travel to the sites on ground and figure out what site is ready for tree harvest. This technology can also be used to calculate the growth rate of forest and detect unhealthy areas of interest.

Updating and creating flood insurance rate maps is another use for lidar technology. By using temporal data during different flood periods, insurance companies know the existent of flooding. This data is used to update old inadequate flood zones. This data will aid insurance companies to determine flood insurance rates and give FEMA and other disaster relief authorities a better idea of where flooding will occur first. Coastal change detection is widely used throughout the United States. Most of the U.S. coastline has been mapped with Lidar. By using lidar change detection on the coast, it can be detected where parts of the coast are affected with deteriorating coastlines and other areas that are collecting the eroded sand. It also shows the effects of Hurricanes and where the sand is moved to. Are the sands deposits moved inland or swept out to sea? This aids the Corps of Engineer to know where to concentrate its efforts to be more efficient in saving the coastlines. By temporally observing the coastline with lidar, it indicates areas prone to Hurricane damage and allows zoning authorities to properly zone properties. The figure below shows the effects of Hurricane Katrina in Dauphin Island, Al [9].

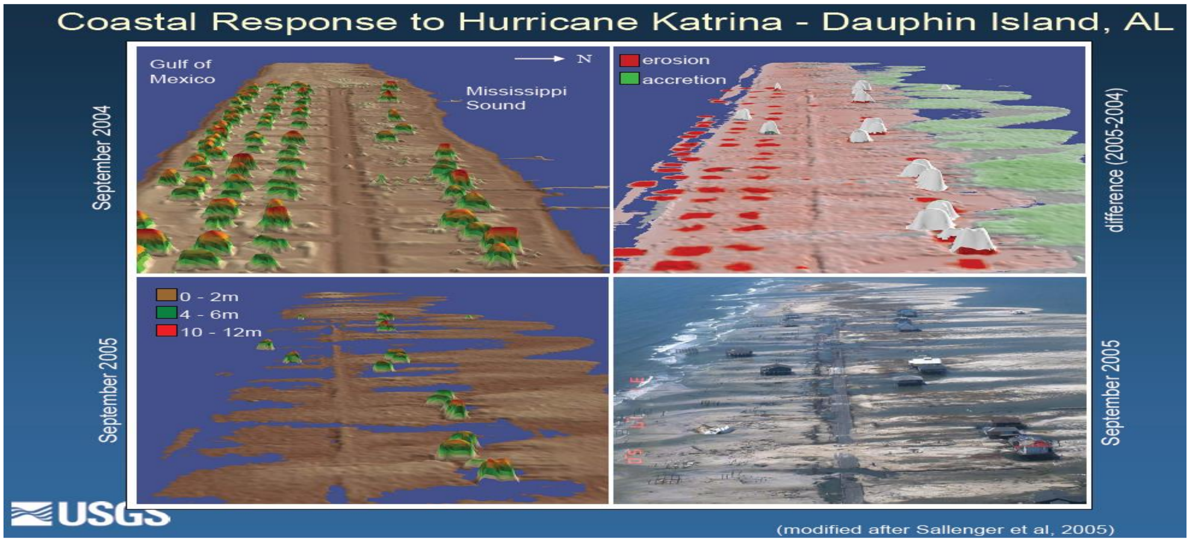


Figure 5: Coastal Change on Dauphin Island, AL before and following Hurricane Katrina

Lidar has revolutionized the mapping industry in Digital Elevation Models. Lidar technology is fast replacing photogrammetric techniques for its accuracy and speed. The U.S. Geological Survey (USGS) used orthorectified images to produce the National Elevation Data (NED). This resulted in an accuracy of 3 meters or 10 feet with a resolution of 10 to 30 meters. [9] Photogrammetric elevation is time-consuming and labor intensive for high accuracy products, so therefore it gets limited updates. There are more hidden areas with this technique, because each ground point must be visible from two separate locations. Currently the cost of lidar is similar to photogrammetry, but the accuracy and speed of producing lidar far outweighs it. Lidar only needs one ground shot to determine the elevation. Lidar is also much more accurate. Lidar can have an accuracy of +/- 10 cm compared to 3 meter accuracy of photogrammetry. [9] The figure below shows examples of airborne lidar from a Helicopter. [4]

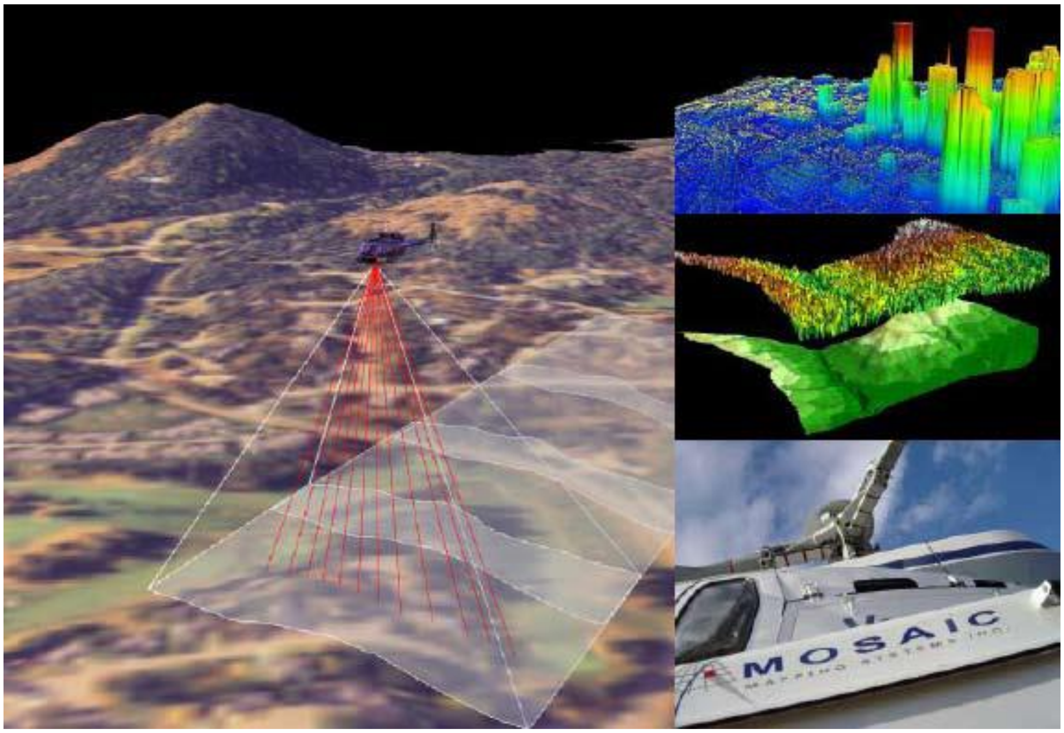


Figure 6: Lidar Airborne data collection and products for surface mapping

Section Three: Mobile Lidar

The next type of LIDAR sensor is vehicle based. This vehicle based lidar is known as mobile scanning or dynamic scanning. It can be placed in a vehicle or boat. A vehicle will drive in the desired project location and take readings. This type of LIDAR sensor also contains a GPS instrument and IMU as well. It can be coordinated with other GPS instruments or pre-surveyed targets. The control or base station points assist in post-processing the LIDAR imagery for correction. For the mobile unit, the IMU system becomes more important than airborne lidar. While collecting data, GPS visibility routinely gets obstructed from buildings and natural features. The IMU gives the mobile system the ability to go through tunnels will still collecting accurate data. The longer the tunnel the more it will affect the accuracy of the data. The point density is more accurate then airborne as well, since the points are closer to the sensor. This results in much denser point cloud. The speed of the vehicle will also change the accuracy as well. The slower the vehicle drives the thicker the point density is. Lidar data can have sub-centimeter accuracy.

There are many uses for this mobile scanning platform in boats and vehicles. Boats are equipped with this technology to map waterway assets. This gives surveyors a ground level and accurate survey of marshes and swamps that cannot be easily mapped on foot. They can also geo-reference semi-submerged rocks with this technology. The Federal Highway Administration has developed a system called the Digital Highway Measurement Vehicle. They use a multi-sensor platform that uses Laser scanners and Macrotexture Lasers to profile the texture of highway surfaces. This system is also being used to explore the use of new 3D ground penetrating radar for subsurface evaluations. This would be very useful in locating utilities and pavement depth. [14] The figure to the right shows a vehicle mounted with a lidar sensor and the figure below is an example of the product produced by it. [4]

Figure 7: Terrapoint TITAN Scanner

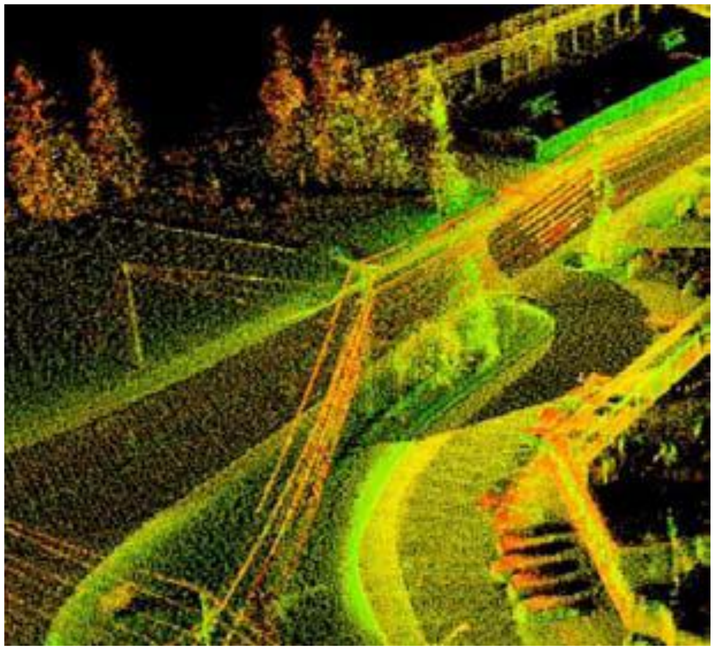


Figure 8: Urban data from Terrapoint TITAN system

Section Four: Terrestrial Lidar

The final type of LIDAR sensor that we will discuss is the ground based or terrestrial sensor. This instrument is similar to a survey instrument, total station that contains the sensor and a GPS device; see figure below. [14] Some instruments include an IMU as well. It will scan the selected area and uses pre-surveyed targets for its alignment and correction. This type of sensor is normally the most time consuming and accurate. There must be at least three control points to serve as references. The instrument itself must be positioned on a control point.

Figure 9: Examples of ground based Lidar Scanners

This type of lidar platform is widely used to survey slope analysis along rock faces along roads. By setting up the instrument in various locations, it can scan the rock face at different angles and slopes. This gives accurate readings with little dead spots. When performing this in a temporal setting, it can indicate rock movement. This can alert the consumer where potential rock slides will occur. It can also show wear and tear on rock surface. This technology has the ability to show where surfaces cracks have formed. With change detection, terrestrial lidar can alarm highway maintenance crews of possible rockslide potential. The figure below shows an example of the scanned rock face using this technology. [14]

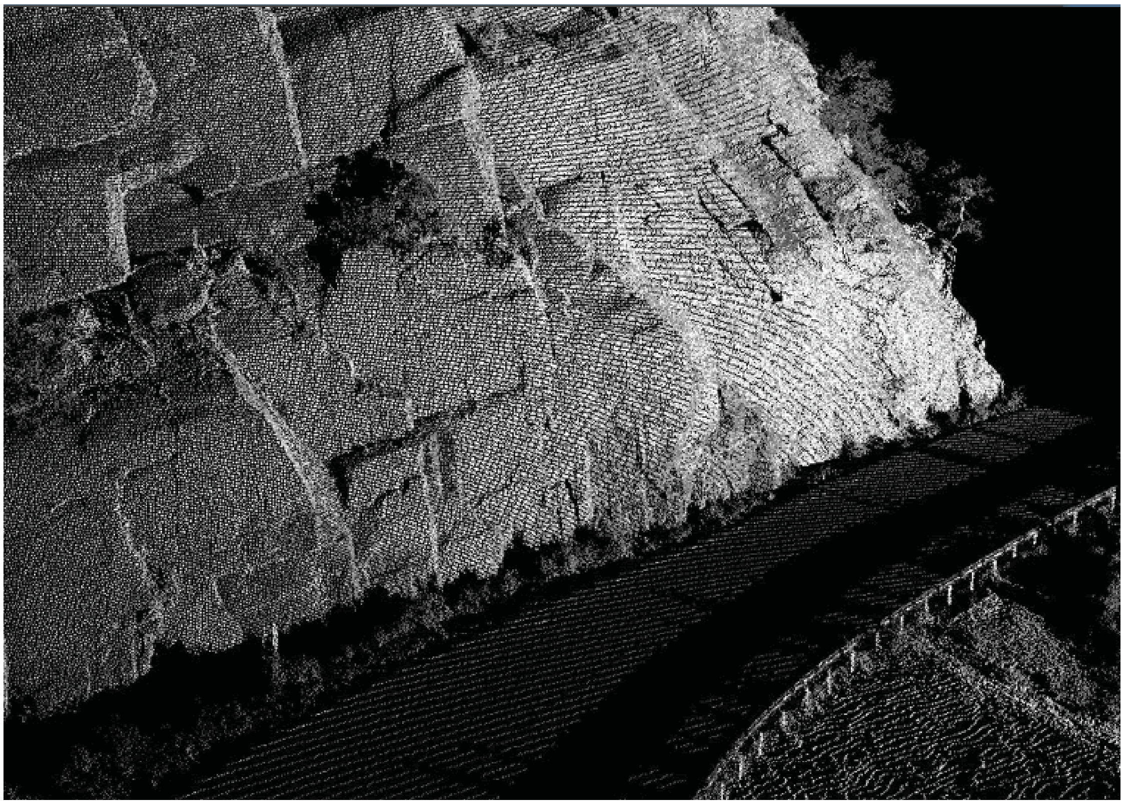


Figure 10: Schematic of point cloud of a rock face along Lemmon Highway, Arizona

CHAPTER 2: GEODESY

Geodesy takes the three dimensional world and puts it into a two dimensional perspective showing features of interest in their correct relative locations, sizes, and orientation for mapping purposes. The earth is not a perfect round sphere so geodesy is this science that is able to apply exact mathematics to this unperfected sphere. Geodesy is the science that determines the size and shape of the Earth. This science is concerned with locating positions on the Earth and determining the Earth's gravity field. There are three respected branches of Geodesy; Geometrical, Physical, and Satellite. [18]

Geometrical geodesy, like its name, is concerned with describing locations in terms of geometry. Coordinate systems are the primary products. Physical geodesy deals with determining the Earth's gravity field, which is crucial for establishing heights. Satellite geodesy is the branch of science that is concerned with using the orbiting of satellites to obtain data for geodetic purposes.

To understand Geodesy better, it may be useful to look at how maps or charts are drawn. A map is a scaled two dimensional image of a region of the earth's surface as seen from above. It shows features of interest in their relative locations, sizes, and orientations. The process usually begins with someone determining positions for all the points of interest. The position is usually a pair or triplet of coordinates. Coordinate system specifies how coordinates are assigned to the real world location.

A Coordinate system enables geographic datasets to use common locations for integration of different points on a map. It is a reference system used to represent the locations of geographic features, imagery, and observations within a common geographic framework. There are two main types of coordinate systems; projected and spherical. A coordinate system is defined by a measurement framework, unit of measurement, definition of projection, and other measurement system properties. A measurement framework is either a geographic or spherical coordinates that are measured from the center of the earth. If it is a planimetric system then it is projected onto a two dimensional planar surface of the earth. The unit of measurement for spherical or geographic is decimal degrees while projected planar system uses either feet or meters. Another method of definition is the actual map projection for the coordinate systems. The last property is the measurement system properties such as a spheroid of reference, a datum, and projection parameters link one or more standard parallel, a central meridian, and possible shifts in the x and y directions.

Section One: GEOID

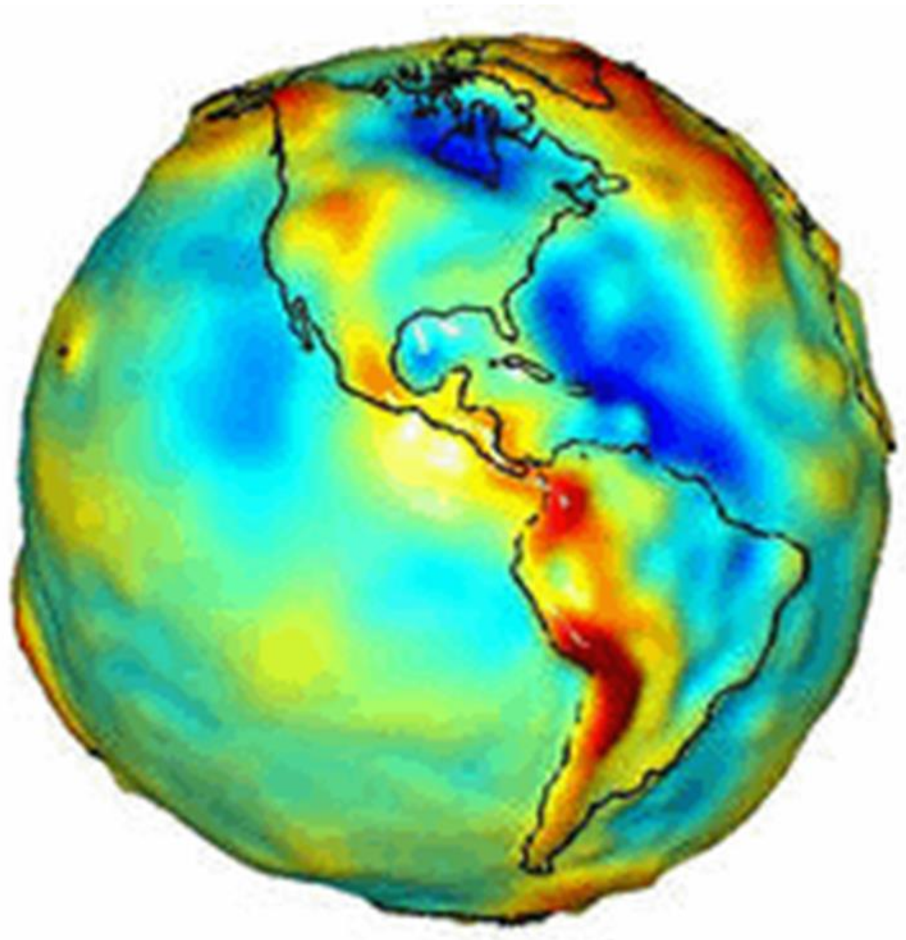


Figure 11: Earth's GEOID Image source: http://bowfell.geol.ucl.ac.uk/~lidunka/GlobalGeophysics/Geophysics2%20-%20Gravity/gravity.htm

The Geoid is a representation of the earth's surface if assumed the sea covered the entire earth. It is also known as the surface of equal gravitational potential or essentially the mean sea level. The geoid surface is an irregular shape of the Earth defined as the true zero surface for measuring elevation.

The GEOID is defined as a surface along which gravity is always equal and to which the direction of gravity is always perpendicular. The issue of the direction always being perpendicular comes into play because optical instruments containing leveling devices are perpendicular to this surface and not the ellipsoidal surface. The geoid is the surface to which the oceans would conform over the entire earth if free to adjust to the combined effect of the earth's mass and centrifugal force of the earth's rotation. This most closely associates itself with Mean Sea Level (MSL).

Since the ellipsoid and geoid are not guaranteed to be parallel, the angle between these two lines represents the deviation of the geoid vertical from the ellipsoid Normal. This causes a problem when surveying with instruments referenced to the horizontal plane by gravity because you are measuring from the geoid but calculating on the ellipsoid.

Section Two: Ellipsoid

The Earth is often thought of as a sphere but its shape is actually closer to an ellipsoid, flattened at the poles and bulging at the equator. The shape of the ellipsoid, or degree of flattening, is determined by comparing radius lengths of the semi-major (horizontal) and semi-minor (vertical) axes.

The Earth has been surveyed many times in an attempt to accurately describe its shape. The surveys have resulted in many ellipsoids, also called spheroids that represent

the Earth. Generally, a spheroid is chosen for a country or region. However, a spheroid that best fits one region is not necessarily the same one that fits another region.
In reality, the Earth is not even a perfect spheroid. Satellite technology has revealed several deviations due to gravity and surface features variations. Satellite-determined spheroids are replacing the older ground-measured spheroids.

Section Three: WGS-84

WGS-84 is a World Geodetic System that is commonly used around the world. With satellite control around the globe, it uses the calculated center of the earth as its starting point.

Section Four: Datum

A datum consists of an ellipsoid, a point of origin (with latitude and longitude) on the ellipsoid from which is the center or starting point for the horizontal control network and a horizontal control network. If the distance and bearing of all unknown points are measured from a known point in the horizontal control network, coordinates can then be computed from these unknown points.

A horizontal datum is a reference frame used to locate features on the earth's surface. It is defined by an ellipsoid and that ellipsoid's position relative to the earth. There are two types of datums: earth-centered and local. An earth-centered datum has its origin placed at the earth's currently known center of mass and is more accurate overall. A local datum is aligned so that it closely corresponds to the earth's surface for a particular area and can be more accurate for that particular area. Within both of the basic types of datums, you can have several global and local datums. Because datums establish reference points to measure surface locations, they also enable us to calculate planar coordinate values when applying a projection to a particular area.

Basically, a datum is an admission of failure. With satellites, mankind can now measure the shape of the Earth within fair accuracy. But before this, people measured the Earth with very long surveys. Everyone knew that the estimates derived from this data were wrong. There are no two geodesists that will ever come up with the same exact figure. In fact, a single geodesist couldn't come up with the same figure twice in a row for example; Clarke 1866 and Clarke 1880. A datum is when surveyors all get together and agree to be wrong. They take a spheroidal model of the earth and fix it to a base point. For North American Datum 1927, NAD27, the United States Geological Survey, USGS, decided that Clarke 1866 was a good approximation and they fixed it at Meade's Ranch, Kansas. Unfortunately, because the datum is wrong and that it is fixed, as one moves away from this point, errors pile up! Hence there are hundreds of datums around the world. Depending on the size of the state in the United States, there can be multiple datums. The United States has approximately one hundred and twenty-four different state plane datums. By having a smaller datum designated in a smaller region will have a higher accuracy in that smaller area. Higher amount of errors spread out the further you get away from the point of origin. By using smaller datums, there is less compounded error in a small area of interest. Here is an example on the amounts of different zones in states. Ohio has two datums, Missouri has three datums, Alaska has ten datums, and

Texas has five different datums. Even a smaller area state like Hawaii has four different datums because the state is spread out over a greater distance. Another note to remember with US state plane datums is that they are typically measured in feet. This can be crucial knowledge if your lidar equipment is measured in meters.

Section 4.1: Same Datum

A critical step with datums is to insure that the reference datum of the area in the field of work is the same as the GPS settings of the lidar equipment. If you are working with multiple datums then the lidar data must be converted into one common datum. Generally choose the datum that represents the majority of the area that work is being conducted. Keeping the data and instruments to the same datum is crucial or a major blunder could occur.

Section 4.2: Convert to common Datum

If you receive a project in a different datum that is in a particular coordinate system, from a particular projection, and referenced to a particular datum that doesn't match any of the products that you are using. There is a much easier solution than you may think. You can simply use one of various different systems that has the ability to convert a coordinate into something more useful to you. This is referred to as Datum Transformation and Coordinate Conversion.

Datum conversions are accomplished by various methods. Complete datum conversion is based on a seven parameter transformation that includes three translation parameters, three rotation parameters and a scale parameter.

Simple three parameter conversions between latitude, longitude, and height in different datums can be accomplished by conversion through Earth-Centered, Earth Fixed XYZ Cartesian coordinates in one reference datum and three origin offsets that approximate differences in rotation, translation and scale.

Section Five: Projection

Map projections are attempts to portray the surface of the earth or a portion of the earth on a flat surface. Think of taking a light source and placing it in the center of the earth and then having a paper on the outside of the globe and how the light of the features of the globe reflects on the sheet of paper. Some distortions of conformality, distance, direction, scale, and area will always result from this process. Some projections minimize distortions in some of these properties at the expense of maximizing errors in others. Some projections are attempts to only moderately distort all of these properties.

Section 5.1: Scale distortions

Scale distortions on a map can also be shown by means of a scale factor (ratio of the scale at a given point to the true scale). Scale distortions exist at locations where the scale factor is smaller or larger than 1. E.g. a scale factor at a given point on the map is equal to 0.99960 signifies that 1000 meters on the reference surface of the Earth will actually measure 999.6 meters on the map. This is a contraction of 40 centimeter per kilometer. [18]

The nominal map scale (given map scale) divided by the scale factor will give the actual scale. E.g. a scale factor of 0.99960 at a given point on a map with a nominal scale of 1:10,000 (one to ten thousand) will give a scale of 1:10,004 (10,000 divided by 0.99960) at the given point. This is a smaller scale than the nominal map scale. A scale factor of 2 at a given point on a map with a nominal scale of 1:10M (one to ten million) will give a scale of 1:5M (10 million divided by 2) at the given point. This is a larger scale than the nominal map scale. [18]

On a secant map projection the application of a scale factor of less than 1.0000 to the central point or the central meridian has the effect of making the projection secant the overall distortions are less than on one that uses a tangent map surface. Most countries have derived there map coordinate system from a projection with a secant map surface for this reason.

Conformality is when the scale of a map at any point on the map is the same in any direction, the projection is conformal. Meridians (lines of longitude) and parallels (lines of latitude) intersect at right angles. Shape is preserved locally on conformal maps. Examples include the Mercator and Transverse Mercator Projections.

Distance on a map is the equidistant when it portrays distances from the center of the projection to any other place on the map. Examples are polar projections.

Direction on a map preserves direction when azimuths (angles from a point on a line to another point) are portrayed correctly in all directions.

Scale is the relationship between a distance portrayed on a map and the same distance on the Earth.

Area is when a map portrays areas over the entire map so that all mapped areas have the same proportional relationship to the areas on the Earth that they represent; the map is an equal-area map.

CHAPTER 3: BASIC TERMINOLOGY

Basic Terminology is necessary and includes technical terms when discussing Lidar that describe the level of accuracy, data collection, and ensuring the proper processing steps. Accuracy is a very important aspect of lidar data.

LAS

Laser file format is commonly seen only by its abbreviation; LAS. LAS file format is a public file format for the interchange of 3-dimensional point cloud data between data users. LAS file format was designed primarily for the exchanging of Lidar point cloud data, but it can be used with any 3-dimesnional data; x,y,z tuplet. LAS is a binary file format. It is not a complex format that maintains information specific to the lidar nature.

RMSE

RMSE is the abbreviation for root mean square error. It is a measurement of the data accuracy similar to the measure of standard deviation if there is no bias in the data.

ACCURACY (Fundamental Vertical Accuracy (FVA))

The Fundamental Vertical Accuracy, FVA, is the measure of the accuracy of data in open areas. It contains a high level of confidence at 95%. The FVA is calculated from the RMSE using the following formula of RMSE times 1.96. [9]

Classification

Classification is when the processed data is defined to the type of object that the pulses have been reflected off. It can be as simple as unclassified if the object not defined to buildings and high vegetation. The most common method is to classify the data set for points that are considered to be bare earth and those that are not bare earth would be unclassified.

Return Number (First/Last Returns)

Most Lidar devices can receive up to five returns from the same Laser source pulse. Many lidar systems are capable of capturing all the returns; first through last. The return number can be used to help determine what the reflected pulse is from ground, tree, brush, etc.

Point Spacing

Point spacing is how close the Laser points are to each other. Pointing spacing is similar to pixel size of an aerial image. It is also referred to as posting density of nominal point spacing. This point spacing determines the resolution of derived gridded products.

Pulse Rate

The pulse rate is the number of discrete Laser shots per second that the lidar instrument is sending out. In 2012, these devices were capable of up to 300,000 pulses per second. It is more common that the data is captured at approximately 50,000 to 150,000 pulses per second. [9]

Intensity Data

The Intensity data is when the Laser return is recorded and the strength of the return is recorded as well. The values are a representation of how well the object reflected the wavelength of light used by the lidar Laser system. The most commonly used commercial topography system in the United States use 1,064 nanometers. This data resembles a black and white photo but cannot be interpreted in exactly the same manner. [9]

GPS (Global Positioning System)

GPS is the quickest and accurate survey method for large product areas. GPS is used to establish ground control points for Lidar. This allows the lidar data to be tied accurately to the surface of the earth. GPS is a much quicker and an accurate method than traditional traverse surveys. Another advantage of GPS data is no need for line of sight surveying between control points. With traditional conventional traverse surveying, the points had to be within sight from each other and without adverse weather. With GPS there is no need to have line of sight survey techniques. GPS receivers only need to have common GPS satellites tracking. The GPS points can be placed and collecting on the east and west coast simultaneously and still properly collect the common data for processing. The weather and time of day does not play much with functionality. GPS satellites are in constant orbit around the earth and sending out signals; 24 hours a day. The only time, GPS is not recommended to be used during lightning storms; which can cause spikes in the GPS signal. Conventional surveys need a clear line of sight; hence in adverse weather conditions this process cannot be performed.

RTK GPS (Real Time Kinematic)

Real Time Kinematic (RTK) GPS survey combines the accuracy of GPS position with speed. RTK uses GPS base stations with radio transmission. The more base stations and if they are evenly surrounding the work area provides the most accurate results. The base stations are positioned on already established survey control points. Each base station has a radio along with the RTK receiver and all the receivers have a common GPS satellite connection. The GPS instruments will get an approximate location with every reading. The base stations will get that reading and provide a shift to the actual position. This shift is applied to the RTK GPS instrument providing an accurate location for the position without the need of post processing it.

DEM, or Digital Elevation Model

Digital Elevation Model, DEM, is a surface created from elevation point data to represent the topography. A DEM is easily used in geographic information systems referred to as GIS or computer-aided design (CAD) application than the raw Lidar point data it is constricted from.

Digital Terrain Elevation Dataset (DTED)

Digital Terrain Elevation Dataset is a digital elevation model that is standard of digital datasets which consist of matrix with terrain elevation values. The data primarily supports various weapon and training systems. DTED is produced into three different levels of detail; DTED level 0, DTED Level 1, and DTED level 2. The horizontal datum for the datasets is the World Geodetic System (WGS 84). The vertical datum for the datasets is the Mean Sea Level (MSL) as determined by the Earth Gravitational Model (EGM). [19]

The accuracy and point spacing depends on the level of detail by each class. DTED level 0 has a horizontal and vertical accuracy of less than 50 meters with a linear error of 90% and point spacing of approximately every 900 meters. DTED level 1 has a horizontal and vertical accuracy of less than 50 meters with a linear error of 90% and point spacing of every approximately 90 meters. DTED level 2 has a horizontal of less than 23 meters and vertical accuracy of less than 18 meters with a linear error of 90% and point spacing of approximately every 30 meters.[19]

Shuttle Radar Topography Mission (SRTM)

The Shuttle Radar Topography Mission was a mission to collect DTED data for over 80 percent of the Earth’s surface. SRTM DTED level 2 has a horizontal of less than 20 meters and vertical accuracy of less than 10 meters with a linear error of 90% and point spacing of approximately every 30 meters. [19]

Processed Data Products

Lidar is an attractive data source for coastal mapping and natural resource management applications. One of the great advantages of lidar technology data products is the ability of products being delivered in several formats. These various formats and their differences of the ways the data are verified and quantified.

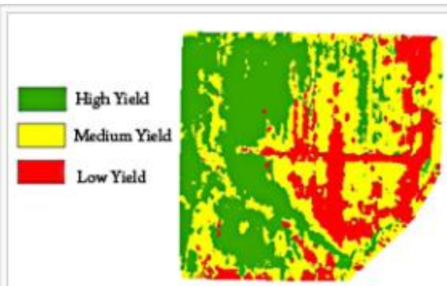
Lidar has made several important improvements from the commonly used previous vertical datasets generated for United States Geological Survey (USGS) topographic quad maps. In the past, National Elevation Dataset (NED) were available that were usually created using photogrammetric techniques. NED had a resulting accuracy of three meters or ten feet with a ten to thirty meter resolution. Elevation data sets generated through Photogrammetric techniques is a time-consuming and labor intensive process especially for high accuracy products. When it takes so much time to build a product in this method, the dataset is not normally updated very often. Another downfall of the photogrammetric technique is that there are hidden spaces under trees where two separate images cannot capture the same point on the ground. This results into outdated NED that has vertical accuracies that limited coastal applications. The cost of lidar is similar to photogrammetry, but it is a more rapid technique that relies largely on this newer technology to produce better results. NED is being updated with lidar data as it becomes available, particularly for the newer 1/9th arc-second, about three meters, resolution NED [9]. As of 2011, only 28% of the United States excluding Alaska had lidar coverage. [9]

CHAPTER 4: APPLICATIONS

Lidar has numerous applications be used through the industries. Most people do not realize the see or utilize lidar technology. Below are several examples of how lidar is aiding our modern day of life.

Agriculture

Every day we eat food and Lidar technology aids in that life basic need. Farmers use lidar to determine which fields need costly fertilizer. They create topographic maps for their fields with lidar which reveals the slope and sun exposure of the farm land. Researchers take the farmland yields results from previous years and compare it with the topographic maps. The farm fields are then categorized into low, medium and high yield areas and this informs the farmer what areas need fertilizer on it to improve the future crop yield. Another application for agriculture is using lidar for crop mapping in orchards and vineyards. Lidar sensors equipped on vehicles can detect foliage growth to determine if pruning or other maintenance needs are required to take place. It can detect the variations in fruit production or perform automated tree counts. Lidar also comes in handy with driverless



Agricultural Research Service scientists have developed a way to incorporate lidar with yield rates on agricultural fields. This technology will help farmers improve their yields by directing their resources toward the high-yield sections of their land.

Figure 12: Agriculture yield example

tractors. In areas that are denied GPS access, in nut or fruit orchards which GPS signals may partially or completely blocked by overhanging foliage, Farm tractors that use GPS can switch to lidar to detect the edges of the rows so that farming equipment can continue until moving back to an area with GPS reception. [13]

Archaeology

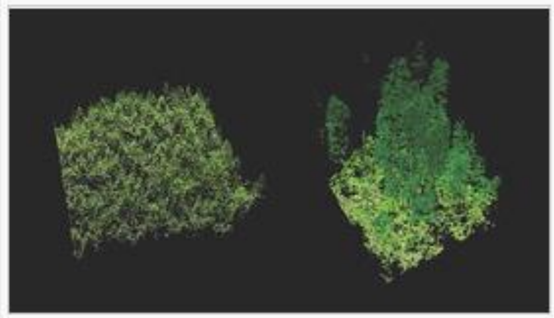
With LIDAR's capability of penetrating vegetation canopy, it has been a huge tool in the field of Archaeology. Lidar has aided in the planning of field campaigns, mapping features beneath forest canopy, and providing an overview of broad, continuous features that may be undistinguishable on the ground. With LIDAR's accuracy it can provide archaeologists with the ability to create high resolution digital elevation models of archaeological sites that can reveal micro-topography that is otherwise hidden by vegetation. Geographic Information Systems can provide analysis and interpretation for lidar derived products. Undiscovered archaeological features below forest canopy can now be mapped. Features that could not be distinguished on the ground or through aerial photography were identified by overlapping hill shades of the digital elevation models created with artificial illumination from various angles. High resolution datasets produced from lidar quickly and relatively cheap can be a huge advantage for this research. It puts the archaeologist in a better position to find what they are searching for with less research time needed. [13]

Autonomous Vehicles

Lidar is being used in the cars we drive today and autonomous vehicles. It is saving lives and preventing car accidents. Some vehicles use lidar for obstacle detection and avoidance to navigate safely through its surroundings utilizing rotation laser beams. Point cloud or cost map outputs from lidar sensors provide the necessary data for robotic software to determine where potential obstacles exist and where the vehicle is from it. Many current vehicles have these sensors that will automatically slow or stop a vehicle when confronted with an obstacle. [13]

Biology and conservation

Forestry has been using many lidar applications. Airborne lidar systems can determine canopy heights, biomass measurements and leaf area. Energy, Railroad and the Department of Transportation is some of the industries using lidar for a faster method of surveying. Topographic maps can easily be generated from lidar surveys for recreational use and producing orienteering maps. [13]



Lidar imaging comparing old-growth forest (right) to a new plantation of trees (left).

Figure 13: Biology and Conservation example

Geology and soil science

Geomorphology, the branch of geoscience concerned with the origin and evolution of the Earth surface topography, has had significant advances from high resolution digital elevation maps generated by airborne and stationary lidar. Detecting subtle topographic features such as river terraces and river channel banks is some of LIDAR's abilities. Lidar technology can measure the land-surface elevation beneath the canopy, spatial derivatives of elevation is better resolved and the ability to detect elevation changes between repeat surveys have enabled novel studies of the physical and chemical processes that shape landscapes. The combination of aircraft based lidar and GPS in the science of geophysics and tectonic movement has been an important tool for detecting faults and measuring the uplift of the earth in the region. Extremely accurate elevation models are the products for these two combined technologies. These models can be accurately produced under heavy tree canopies. Monitoring of glacial movement utilizes the technology of lidar. It can detect subtle amounts of growth, decline, and movement of these glaciers. Detailed terrain modeling is used for coastal change detection; slope changes and landform breaks which perform patterns in soil spatial relationships. [13]

Atmospheric remote sensing and meteorology

Atmospheric remote sensing and meteorology initially was based on ruby Lasers. Meteorological applications represent one of the first applications of laser technology. Lidar was constructed shortly after the invention of the laser. The capabilities of lidar technology has vastly expanded the capabilities the systems can perform a range of measurements that include profiling clouds, measuring winds, studying aerosols and quantifying various atmospheric components. Surface pressure, greenhouse gas emissions, photosynthesis, fires, and humidity are all useful information provided by atmospheric components. Surface pressure is determined by measuring the absorption of oxygen or nitrogen. Greenhouse gas emissions are the measurement of carbon dioxide and methane. The measurement of carbon dioxide determines the amount of photosynthesis. Information on fires is through measuring carbon monoxide and humidity is from the amount of water vapor. [13]

Atmospheric lidar remote sensing works in two different ways by measuring the backscatter from the atmosphere and the scattered reflection off the ground, when airborne lidar is used, or other hard surfaces. Backscatter from the atomsphere gives a direct measurement of clouds and aerosols. From backscatter, derived mearurements such as winds or cirrus ice crystals require careful selection of the wavelength and / or polarization detected. Rayleigh Doppler Lidar and Doppler Lidar are referenced on your local news channel, they are used to measure temperature and / or wind speed along the beam by measuring the frequency of the backscattered light. [13]

A FASOR used at the Starfire Optical Range for lidar and laser guide star experiments is tuned to the sodium D2a line and used to excite sodium atoms in the upper atmosphere.

Figure 14: FASOR

Law Enforcement

One of the uses for Lidar you may not appreciate is the lidar speed gun. Next time you get pulled over you can thank lidar technology for that. Lidar devices are designed to automate the entire process of speed detection, vehicle identification, driver identification and evidentiary documentation. Lidar has a narrow beam that easily targets and individual vehicle. This eliminates the need for visual estimation. It records an image of the license plate at the same instant as recording the speed violation. It takes half a second to estimate the speed giving little warning to the offending vehicle. Lidar can also measure the distance between vehicles for tailgating purposes if the other vehicle is not in the shadow of the first car. [13]

Police officer operating a hand-held lidar speed detection device.

Figure 15: Lidar speed detection

Mining

The mining industry uses lidar for various tasks. With lidar data, the calculation of ore volumes is accomplished. Periodically, normally monthly, areas of ore removal are scanned then compared to surface data of previous scans for the calculation of ore volume removed. Lidar sensors can also be used for obstacle detection and avoidance for robotic mining vehicles. [13]

Physics and Astronomy

Observatories in a worldwide network use lidar technology to measure the distance between the observatories and reflectors placed on the Earth's moon. The distance is measured to millimeter precision and tests of general relativity. The Mars Orbiting Laser Altimeter uses a lidar instrument in a Mars orbiting satellite that produces a precise global topographic survey of the Mars surface. NASA's Phoenix Lander used lidar technology in September 2008 to detect snow in the Mars atmosphere.

In the science of atmospheric physics, lidar is used as a remote detection instrument. It measures densities of certain constituents of the middle and upper atmosphere; potassium, sodium, or molecular nitrogen and oxygen. Temperatures are calculated with these measurements. Lidar technology is used to measure wind speed as well as provides information about vertical distribution of the aerosol particles. [13]

Rock mechanics

Lidar technology has been widely used in rock mechanics for slope change detection and rock mass characterization. With three-dimensional point clouds, some important geomechanical properties from the rock mass can be extracted with lidar. Many of these properties include discontinuity orientation, discontinuity spacing and rock quality designation, discontinuity aperture, discontinuity persistence, discontinuity roughness, and water infiltration. The geomechanical quality of the rock mass through the Rock mass rating index has been assessed with these properties. Using existing methodologies, orientations of discontinues can be extracted, it is then possible to access the geomechanical quality of a rock slope through the slope mass rating index. In addition, by comparing historical data of different three-dimensional point clouds from the slopes acquired can produce a change detection of time interval to predict rock falls or any other land sliding processes. [13]

Robotics

Robotics is using lidar technology for the perception of the environment as well as object classification. Three-dimensional elevation maps of the terrain are provided by lidar technology. Lidar technology can also produce high precision distance to ground and approach velocity that can enable safe landing of robotics and manned vehicles with high degree of precision. [13]

Spaceflight

Spaceflight is utilizing lidar technology for range finding and orbital element calculation of relative velocity in proximity operations and station keeping of spacecraft. Lidar technology is also used for atmospheric studies from space. Lidar devices sends out short pulses of Laser light beamed from a spacecraft that can reflect off of tiny particles in the atmosphere and back to the telescope aligned with the spacecraft lidar device. With lidar’ s ability for precisely timing the lidar echo and by measuring how much Laser light is received back to the telescope, scientists can accurately determine the location, distribution and nature of the particles being observed. This creates a revolutionary new tool for studying constituents in the atmosphere; from cloud droplets to industrial pollutants that are typically difficult to detect by other means. [13]

Surveying

Lidar has revolutionized surveying in two major ways; airborne and terrestrial lidar. With using survey control points, airborne lidar can blanket a large area with control points that are tied to the survey points. In terrestrial lidar, a surveyor can use a terrestrial lidar device to scan the whole viewable area and tie them to control points. With both types, there is no need in putting control on every point needed. A survey grid of control points can be laid out evenly spaced in an area of interest and the lidar will fill them all in with quality horizontal and vertical control points.

Transport

The railroad industry has been using lidar to generate asset health reports for asset management and by various departments of transportation to assess their road conditions. You can see in current automobiles that many are equipped with an adaptive cruise control (ACC). A lidar device is mounted in the front of the vehicle and monitors the distance between the vehicle and the vehicle in front. If your vehicle gets too close to the vehicle ahead then it will automatically apply the brakes to slow the vehicle down. Once the vehicle ahead is at a safe distance or clear it will allow the vehicle to accelerate again. [13]

Wind farm optimization

Wind farms are using lidar technology to increase the energy output by accurately measuring wind speeds and wind turbulence. The nacelle is the name for the generator and gearbox shell with the rotator shaft can have an experimental lidar system. This system is mounted on the wind turbine or integrated into the rotating spinner to measure oncoming horizontal winds, winds in the wake of the wind turbine, and proactively adjust blades to protect components and increase power. Lidar can also be used to characterize the incident wind resource for comparison with wind turbine production and verified with the performance of the wind turbine by which the wind turbine's power curve is measured. [13]

Solar Photovoltaic deployment optimization

Assist planners and developers in optimizing solar photovoltaic systems use lidar to determine appropriate rooftops and for determining shade loss. They tend to focus on building facades for solar potential estimation. They also look at the surrounding area and consider the shading from vegetation and larger surrounding terrain.

CHAPTER 5: PROCESSING LIDAR

While processing lidar, like many datasets, there are required and recommended methods to process raw data to a finished lidar product. Depending on the type of final product will require different procedures. The first procedure for processing Lidar data is to check the quality of the lidar data. Next, you will prepare the data for the final product. Once your data is prepared then you can derive your final product for the customer's need. Finally, you may need to edit these products for any anomalies or clean them up for a crisper final product. For these exercises, I used LAStools to process the lidar data. You can use LAStools as a GUI or through ArcGIS. For these exercises, I used the GUI process.

Section One: Quality checking

The first step with processing Lidar data is to check the quality of the lidar data. After downloading the data, we will view the data to inspect the area of interest. Check to see if all the data is connected in the correct area and see if there are any voids. The next step for multiple flight lines is to check the flight line overlap plus the vertical and horizontal alignment. If you have survey control points in the area then you can check the data between the survey data and lidar data.

Section 1.1: Viewing the data

I used the LASView executable command for the GUI window. LASView is a simple viewer for Lidar in LAS, LAZ, or ASCII format. It can also edit or delete points in this GUI. Finally you can compute and display a TIN from a selection of the lidar points.

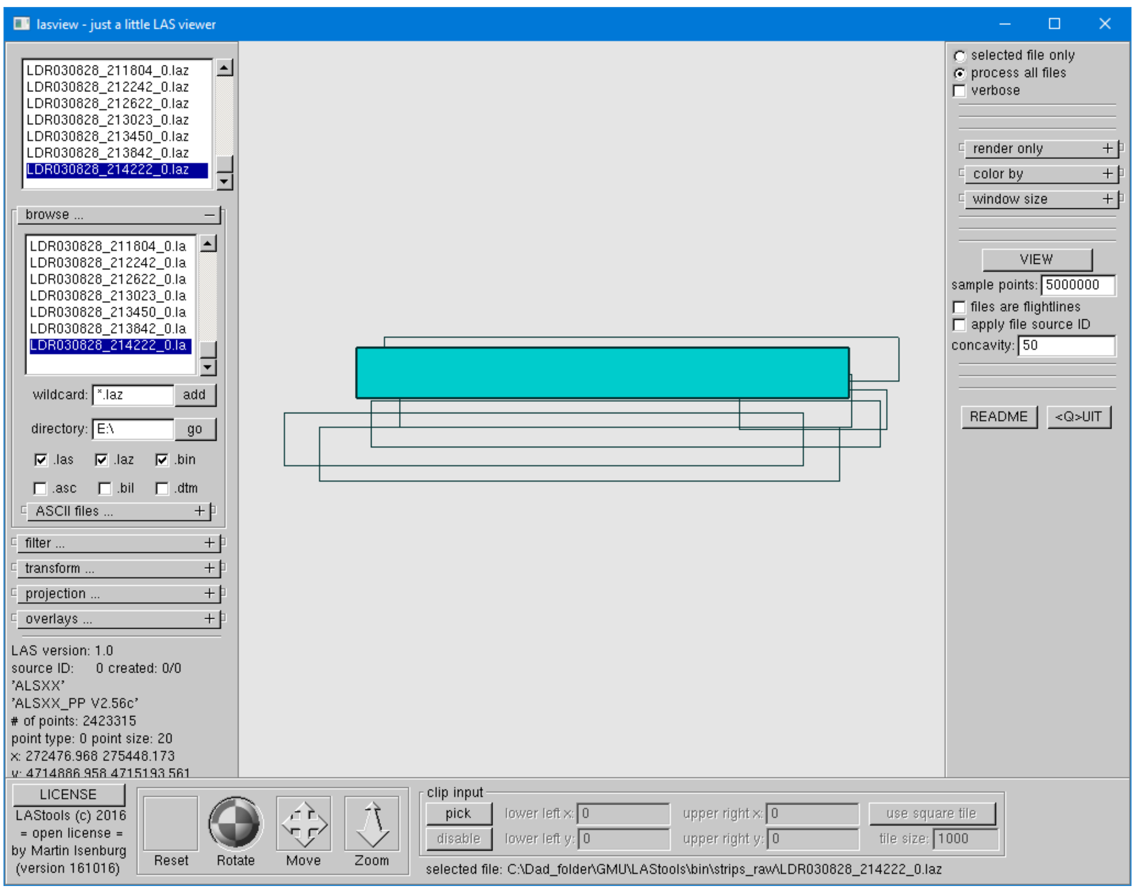


Figure 16: LASView GUI

To view the data press View on the right side. I also changed it to 10 million points.

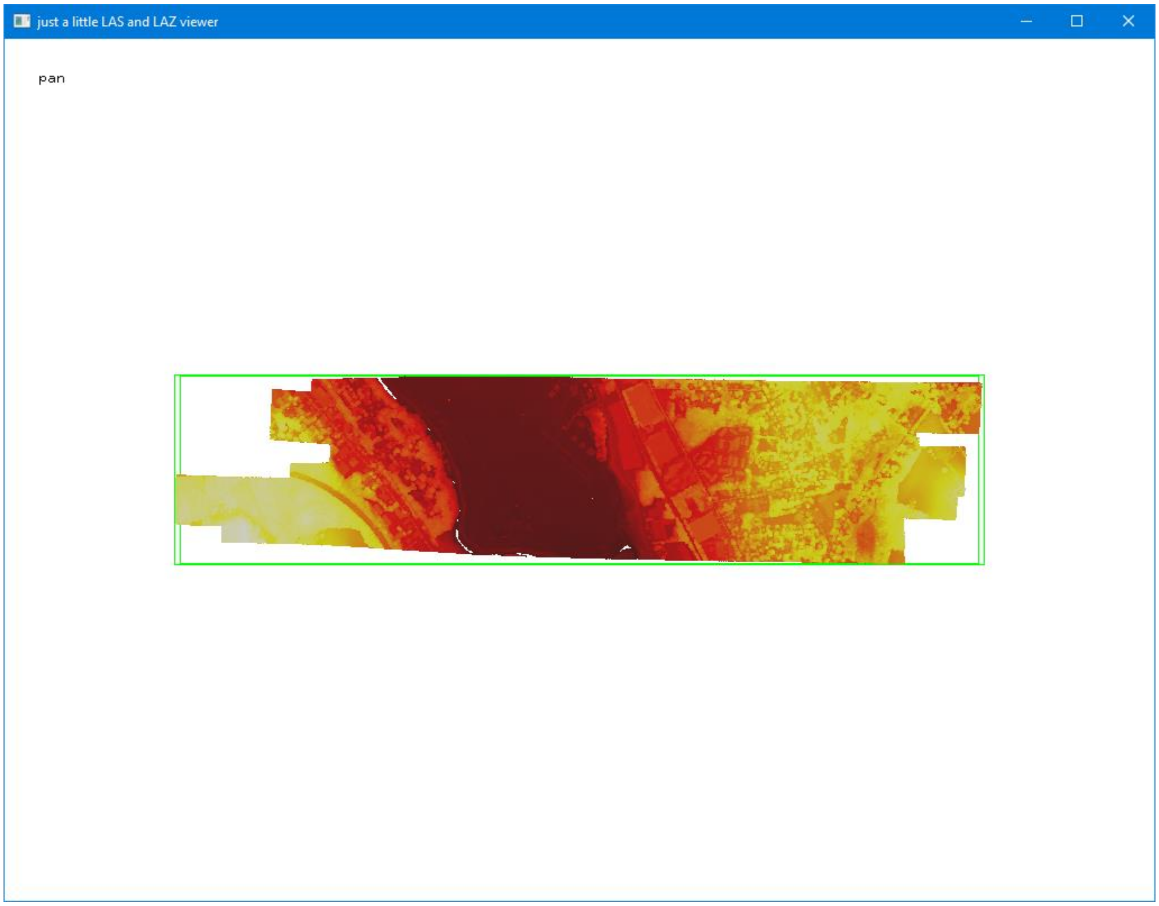


Figure 17: LASview Image

Section 1.2: Checking for overlap and voids

LASoverlap reads Lidar points from LAS, LAZ, ASCII, Bin, or Shp files. Using LAS Overlap, it will produce a PNG output as well as a KML file that allows visualization of the overlap and difference rasters within the geospatial context of Google Earth. Look for void areas in the overlap. This could be evidence of serious errors in the data caused by poor flight plans. Areas that are not potential problems are deeply blue or deeply red saturated areas that are not in water bodies but non-forested terrain. If there are major voids, then this data should be sent back to the vendor.

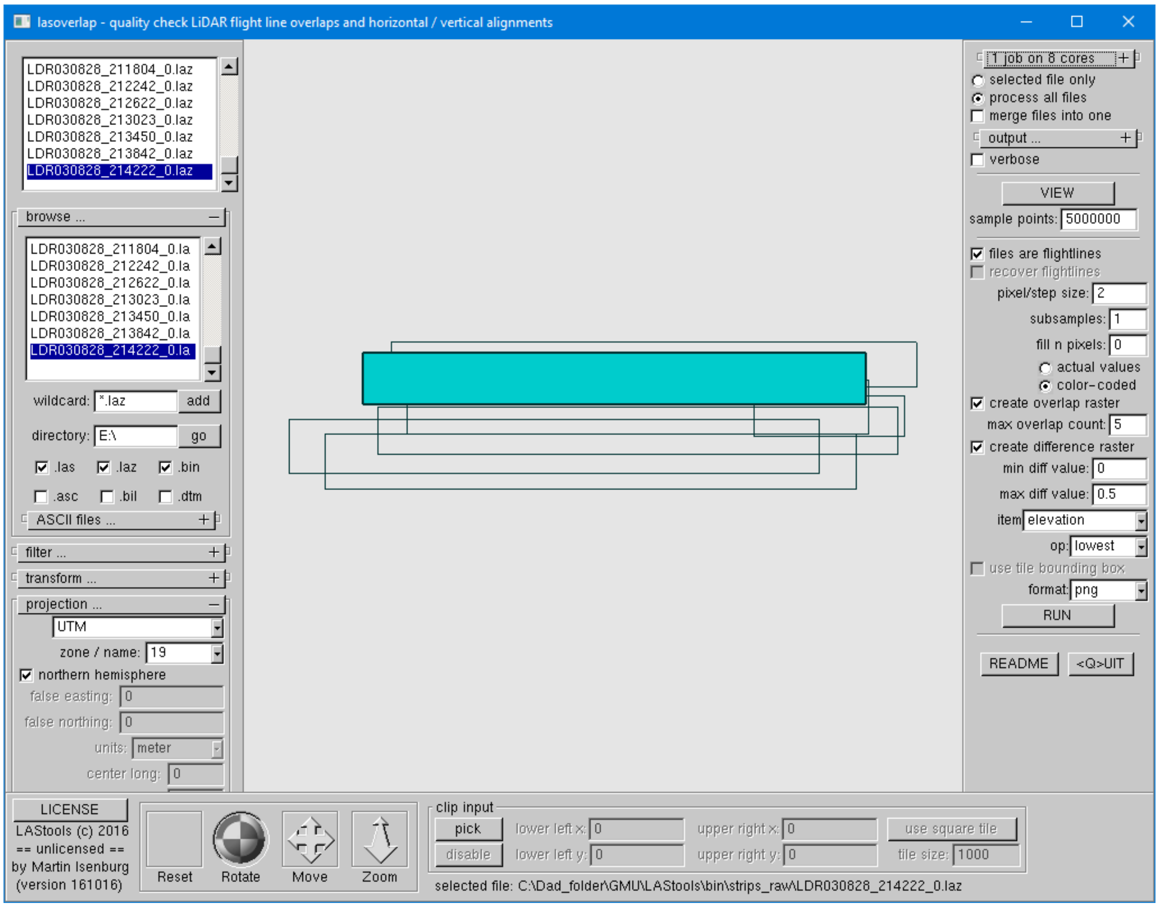


Figure 18: LASOverlap GUI

Section 1.3: Checking control with lidar

LAS Control computes the height of the lidar at control point locations and reports the height difference between the two. It will read lidar data in LAS, LAZ, and ASCII format and triangulates the relevant points into a TIN. Now, we will compare the

Lidar elevation with a set of 29 exactly known control points. These points were obtained through a ground survey. We will use LAS Control to check the data.

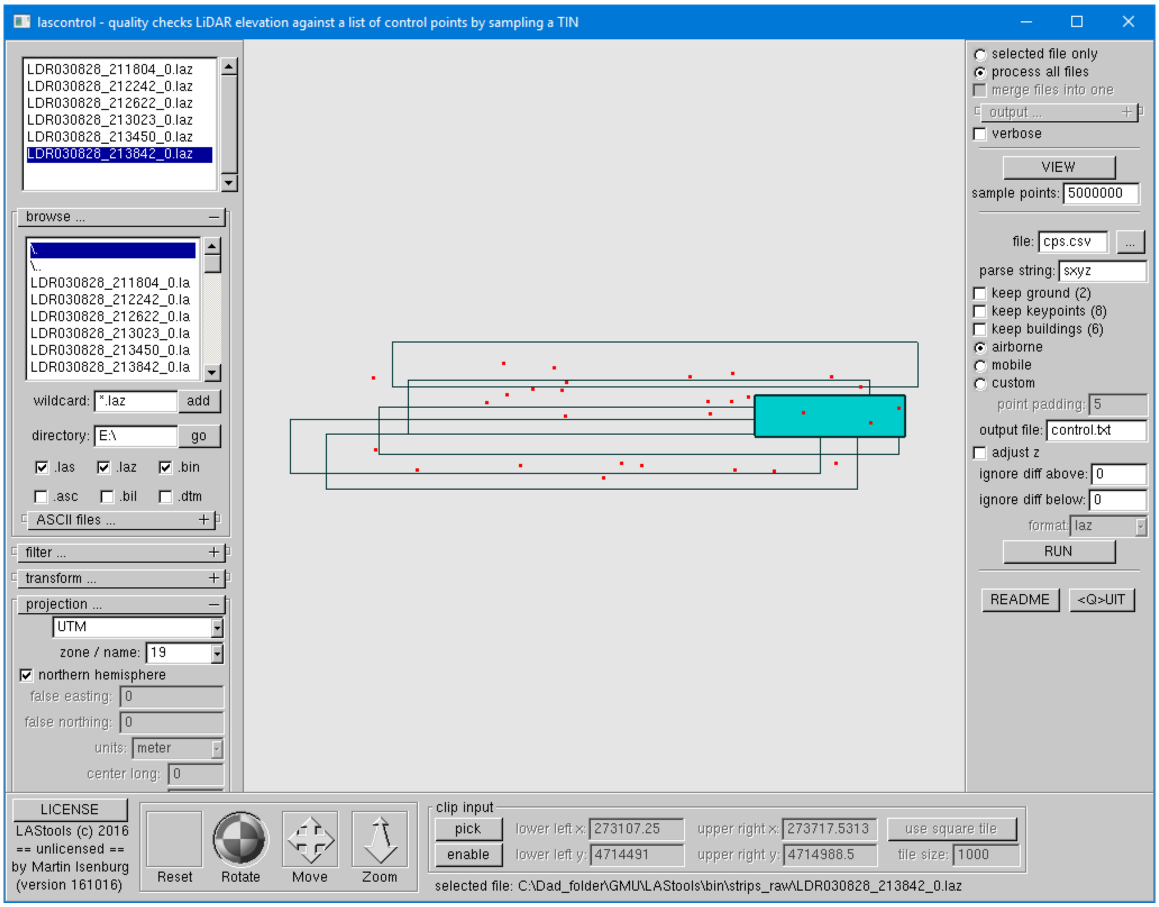


Figure 19: LAS Control GUI

By selecting a small portion of the data and then viewing it you can see how the points line up. The lidar was seen triangulated and turned to get a more 3D view.

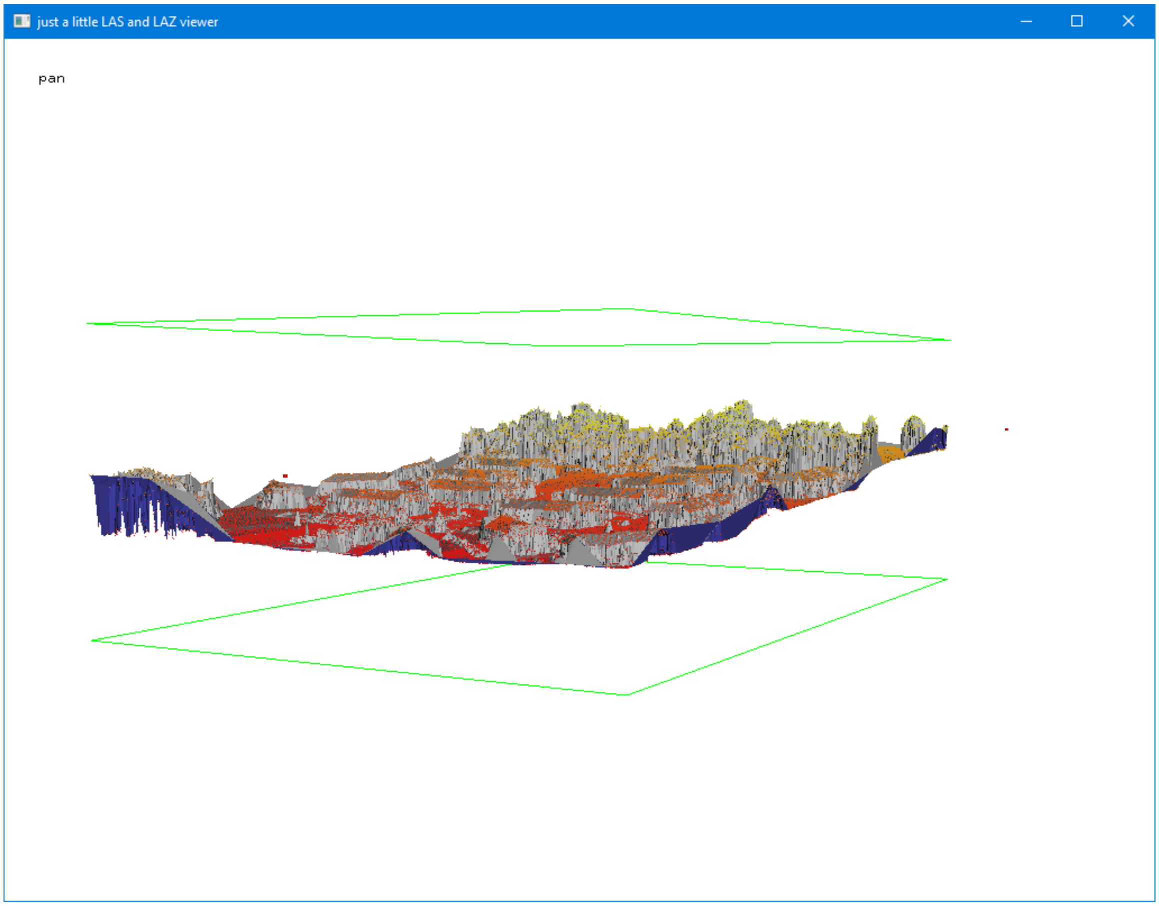
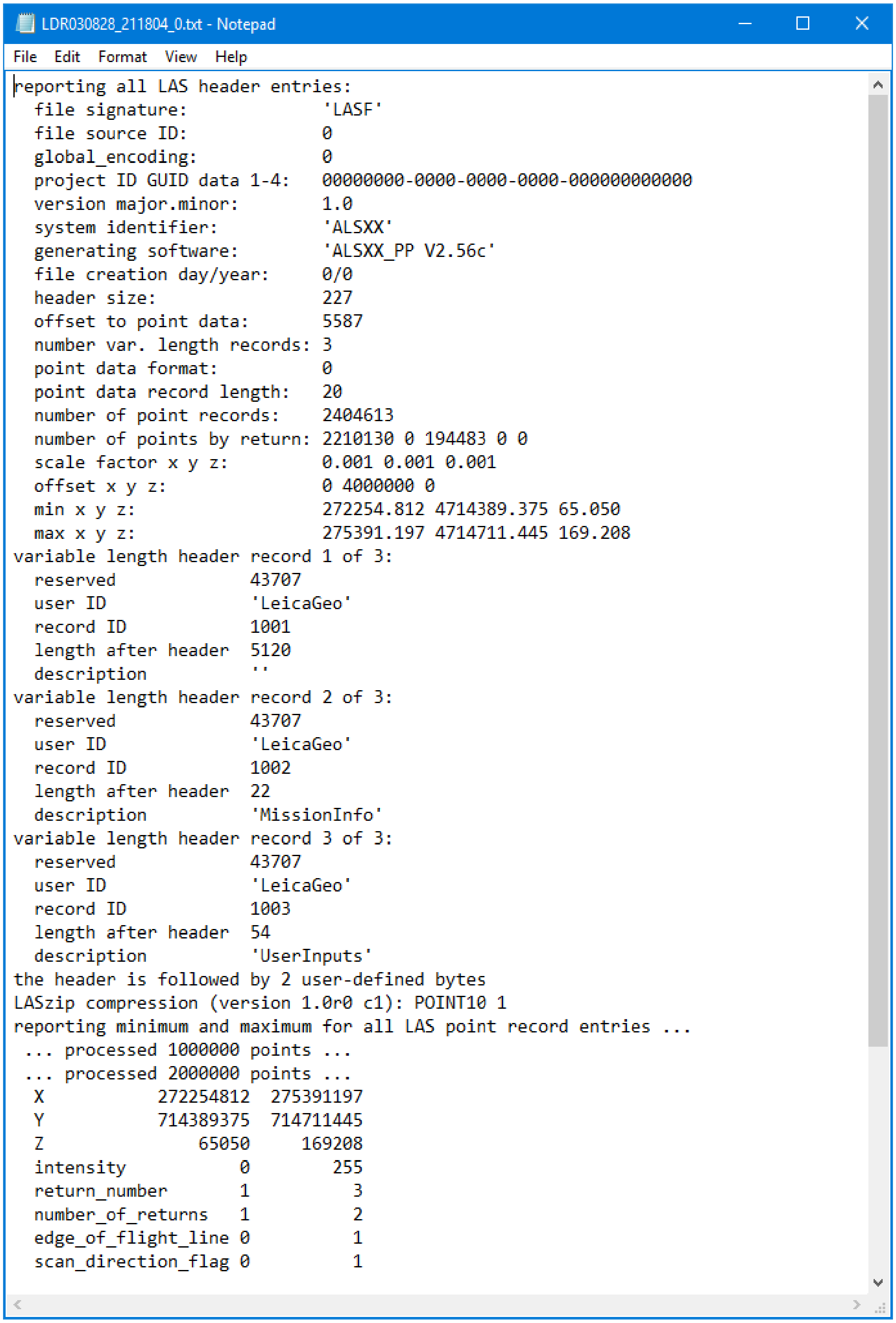


Figure 20: LASView of control

Section 1.4: Report of data

LASInfo reports the contents of the header, Variable Length Record (VLR) and provides a short summary of the lidar points. The tool will warn you if there is a difference between the header information and the point content for counters and bounding box extent.




```
reporting all LAS header entries:
  file signature:             'LASF'
  file source ID:             0
  global_encoding:            0
  project ID GUID data 1-4:   00000000-0000-0000-0000-000000000000
  version major.minor:        1.0
  system identifier:          'ALSXX'
  generating software:        'ALSXX_PP V2.56c'
  file creation day/year:     0/0
  header size:                227
  offset to point data:       5587
  number var. length records: 3
  point data format:          0
  point data record length:   20
  number of point records:    2404613
  number of points by return: 2210130 0 194483 0 0
  scale factor x y z:         0.001 0.001 0.001
  offset x y z:               0 4000000 0
  min x y z:                  272254.812 4714389.375 65.050
  max x y z:                  275391.197 4714711.445 169.208
variable length header record 1 of 3:
  reserved             43707
  user ID              'LeicaGeo'
  record ID            1001
  length after header  5120
  description          ''
variable length header record 2 of 3:
  reserved             43707
  user ID              'LeicaGeo'
  record ID            1002
  length after header  22
  description          'MissionInfo'
variable length header record 3 of 3:
  reserved             43707
  user ID              'LeicaGeo'
  record ID            1003
  length after header  54
  description          'UserInputs'
the header is followed by 2 user-defined bytes
LASzip compression (version 1.0r0 c1): POINT10 1
reporting minimum and maximum for all LAS point record entries ...
 ... processed 1000000 points ...
 ... processed 2000000 points ...
  X            272254812  275391197
  Y            714389375  714711445
  Z                65050     169208
  intensity            0        255
  return_number        1          3
  number_of_returns    1          2
  edge_of_flight_line  0          1
  scan_direction_flag  0          1
```

Figure 21: LASInfo results

Section Two: Data Preparation

After conducting the quality checks on your lidar data, it is time to prepare the lidar data for analysis. If you have flight path lidar strips then the first thing you would do is tile your data to avoid overlapping data. Next step we will process the data for bare earth extraction. This tool was designed for mainly airborne lidar but can be used for terrestrial lidar as well. After bare earth extraction we will calculate the height of each LAS point above the ground. Finally, we will classify the data by height and surrounding lidar point geometry. It requires that the bare earth extraction and elevation of each point was calculated. The tool will classify points as ground points, buildings, vegetation, or unclassified points which could possibly be noise.

Section 2.1: Tiling the data

LASTile takes potentially very large amount of LAS points from one or many files into square non-overlapping tiles of a specific size and save them into LAS or LAZ format. There are two main reasons for square tiling. The first reason is that it is by far the most common way that LAS files are tiled for archival or distribution. The next reason, it will eventually be exploited by our streaming TIN generation code to seamlessly Delaunay triangulate large amounts of tiles in a highly memory-efficient fashion. LASTile adds a small VLR to the header of each generated LAS/LAZ tile that stored its index or its finalization tag in the square quad tree.

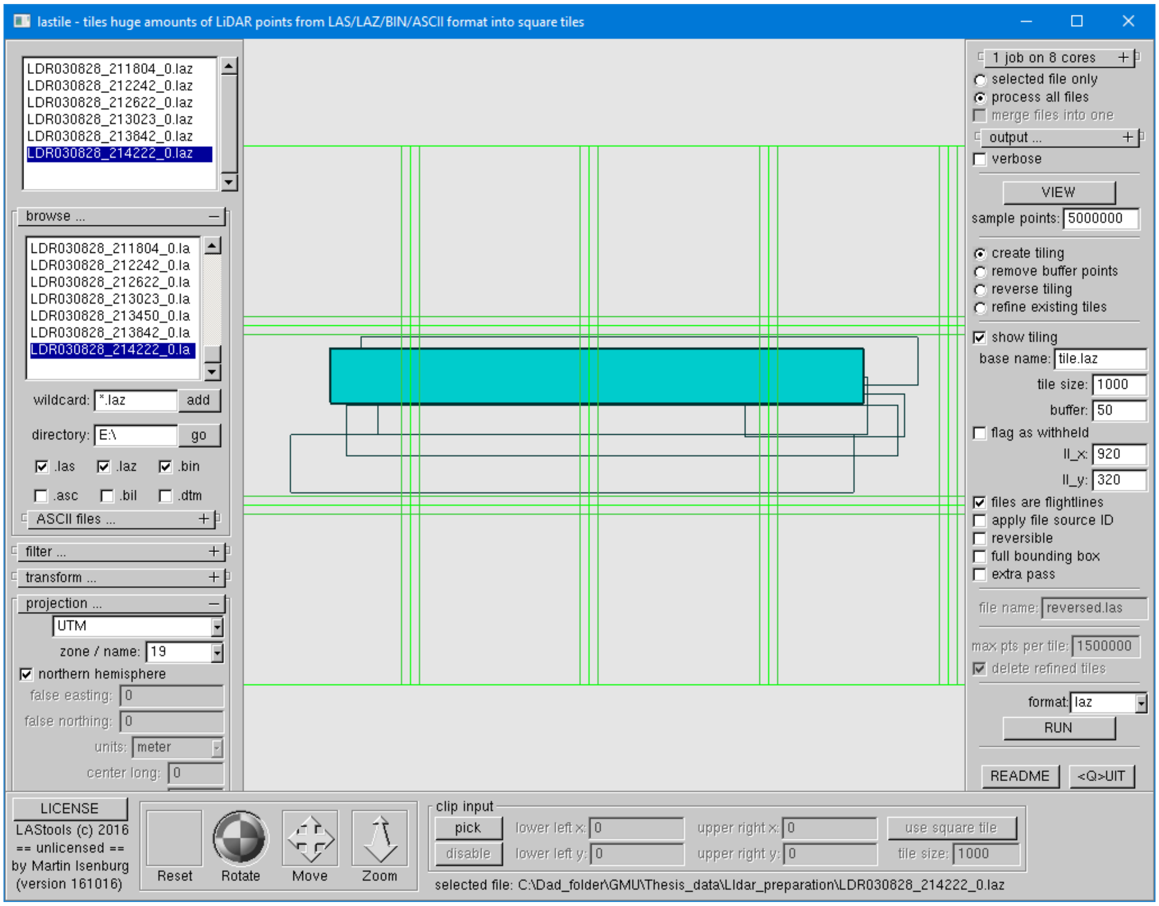


Figure 22: LASTile GUI

Section 2.2: Bare earth extraction

We took the seven tiles and created four quad tiles. Next we will use LASGround for bare earth extraction. It classifies the LIDAR points into ground points, class = 2, and non-ground points, class = 1. This tool works very well in natural environments such as mountains, forests, fields, hills, or other terrain with few man-made objects. LASGround program was designed primarily for airborne lidar.

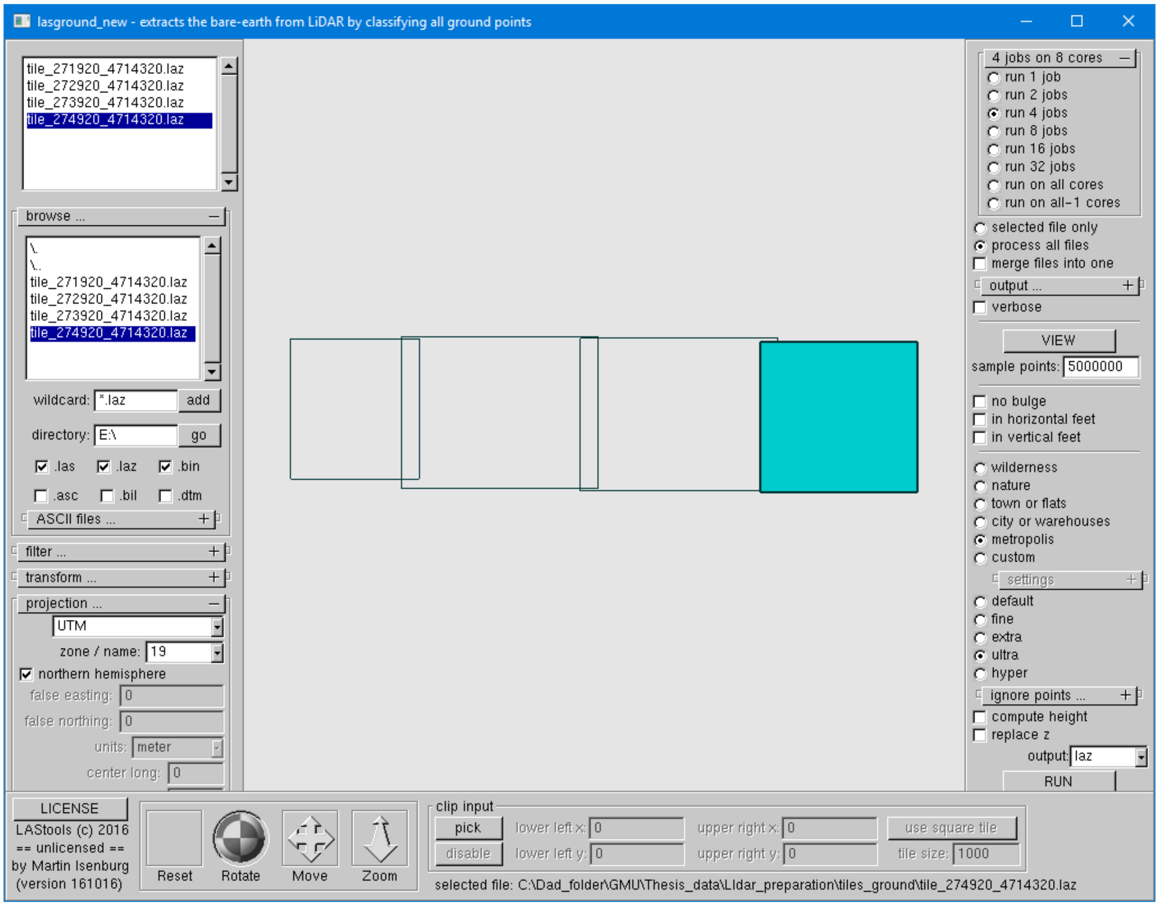


Figure 23: LASGround GUI

Next we will use LASview to inspect the results of the bare-earth classification.

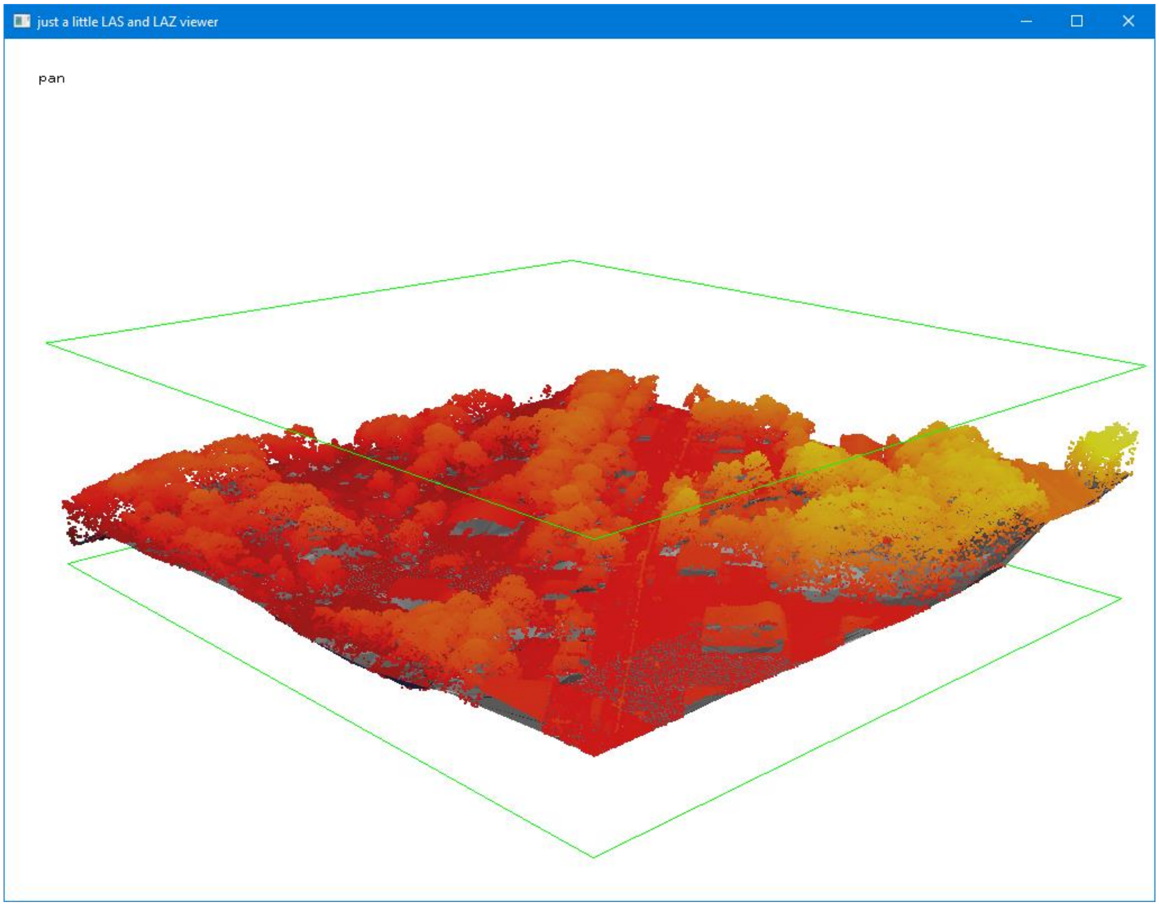


Figure 24: LASGround View

Section 2.3: Computing vertical height of points

There are dirt points below the ground and air points far above the ground. We can remove these points using LASHeight. This process computes for each point the vertical distance to the triangulation of the ground points and stores it in the user data field. We also need these heights for finding buildings and vegetation.

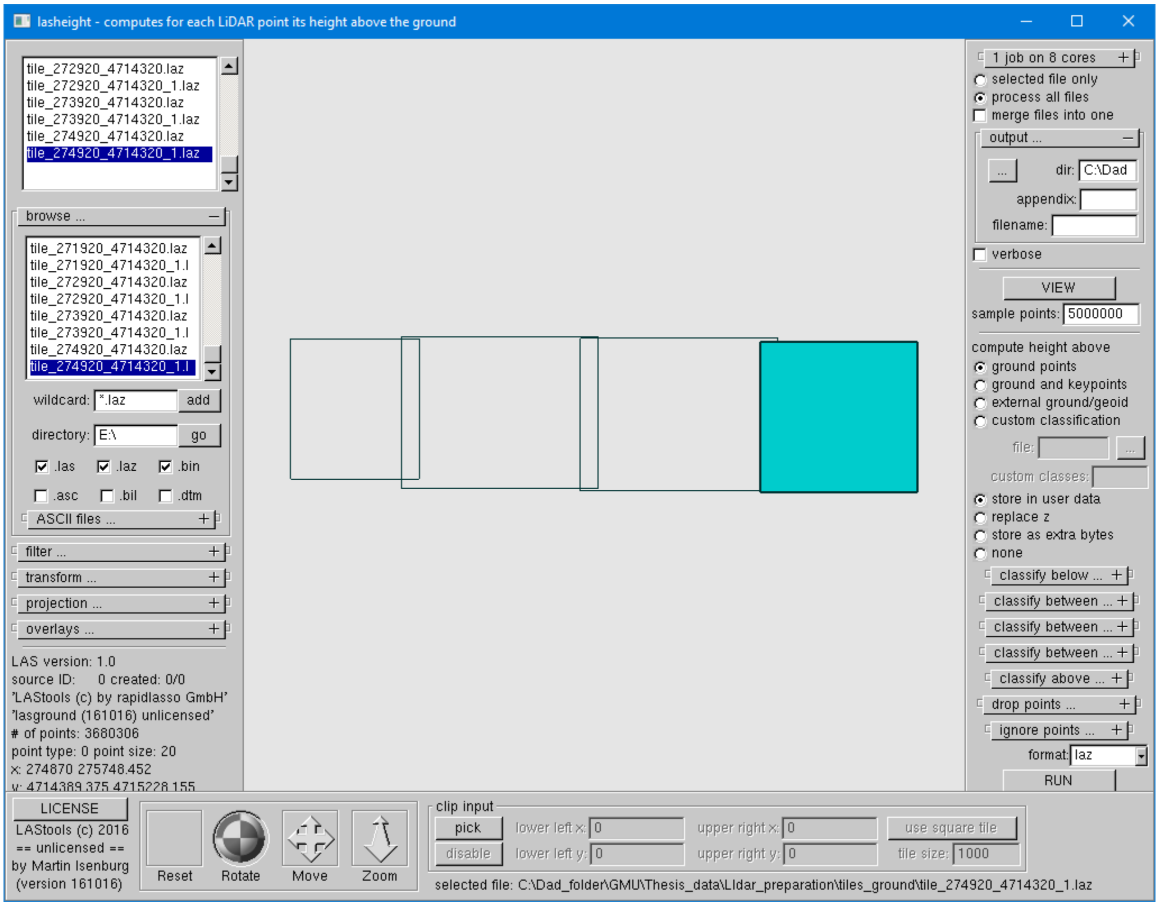


Figure 25: LASHeight GUI

Section 2.4: Classify the lidar points

Next stage we will classify the Lidar tiles with ground, building, unclassified and vegetation points. This tool requires that the bare-earth points have already been identified and that the elevation of each point has been calculated. Essentially the tool finds neighboring points that are at least 2 meters above the ground and if it forms a planar line for a roof or rugged form for vegetation. We will use the LASClassify tool.

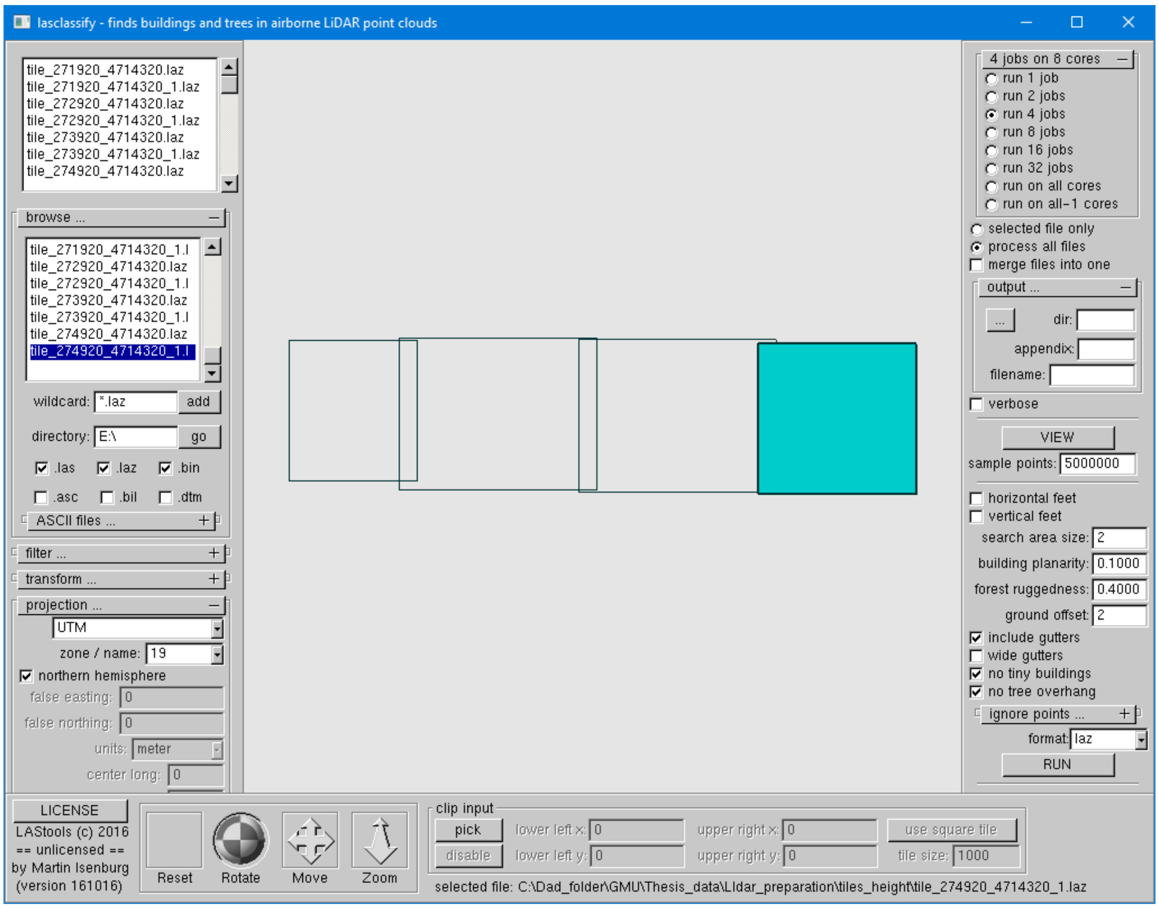


Figure 26: LASClassify GUI

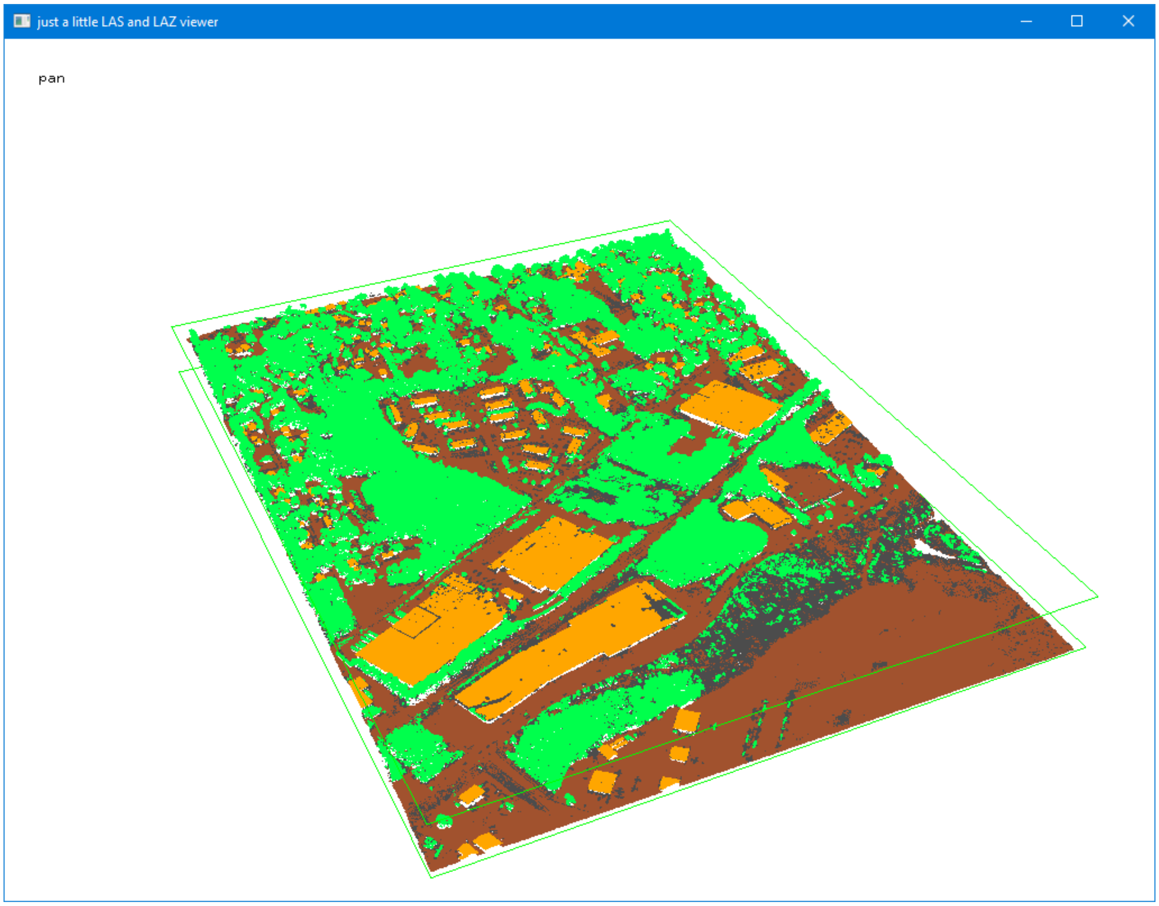


Figure 27: LASClassify View

We will finalize the data using LASTile. With the final dataset we will store the data without the 50 meter buffers. This process removes the buffers that were added in the very beginning and carried through all the processing steps to avoid artifacts along the boundaries.

Section Three: Derivative Production

After we performed our quality checks and prepared our data, we are ready to create our final products. In this chapter, we will create DTM and DSM from classified data. Then we will read the lidar data from the LAS, LAZ, or ASCCI formats and create grids into a raster dataset. We will also create a seamless TIN from lidar points in the LAS or LAZ format. It is typically used for hillshade products. Finally we will discuss how to create contour lines.

Section 3.1: Generating DTM

Next, we will generate matching DTM tiles without edge artifacts. We are going to use the LAS2dem tool to create raster's from Lidar by triangulating the points and then sampling the resulting TIN at the center of each raster pixel. For the DTM, we will have the tool filter the data by only looking at ground points and thin the data by only keep one point for every 0.5 by 0.5 meter square to decrease the storage space needed.

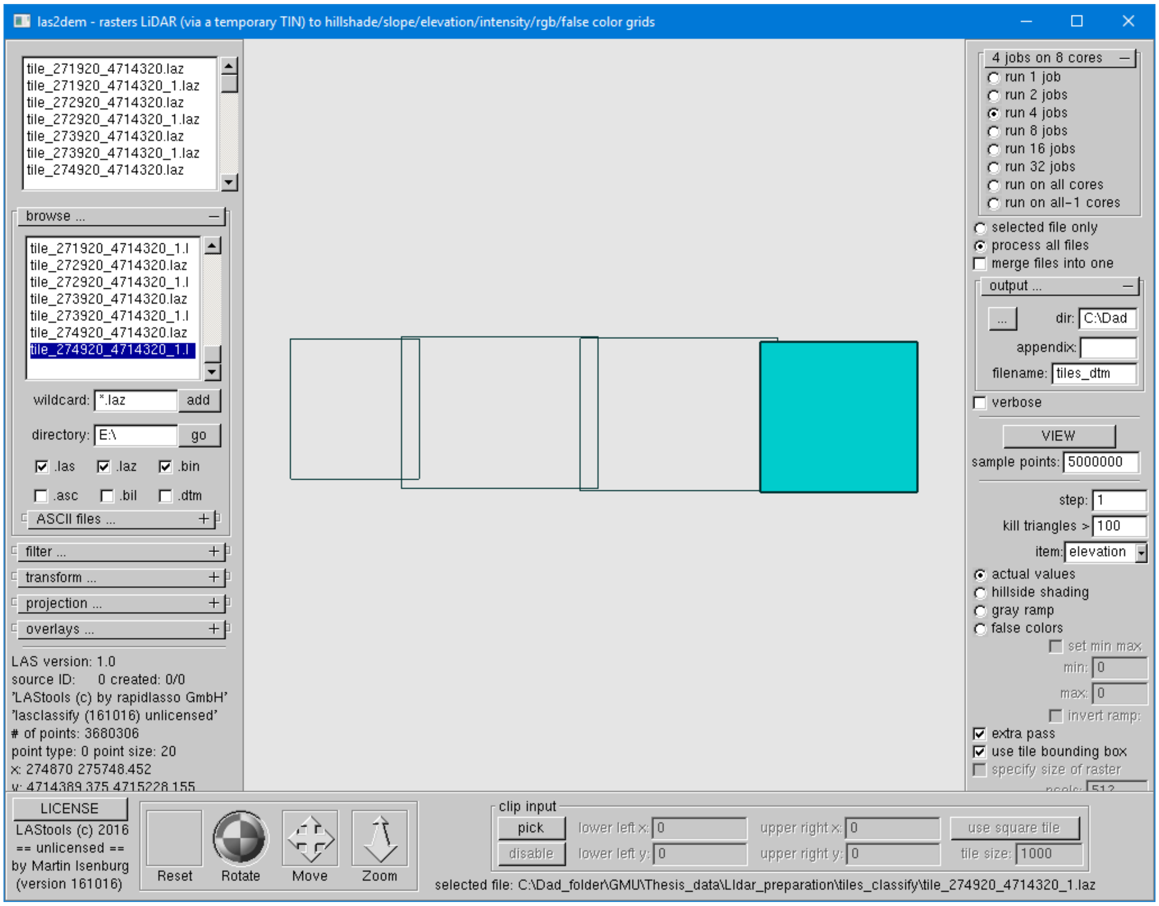


Figure 28: LAS2Dem DTM GUI

Section 3.2: Generating DSM

Now, we will generate matching DSM tiles. We are going to use the LAS2dem tool to create raster's from Lidar by triangulating the points and then sampling the resulting TIN at the center of each raster pixel. For the DSM, we will have the tool filter the data by only looking at the first returns and thin the data by only keep one point for every 0.5 by 0.5 meter square to decrease the storage space needed.

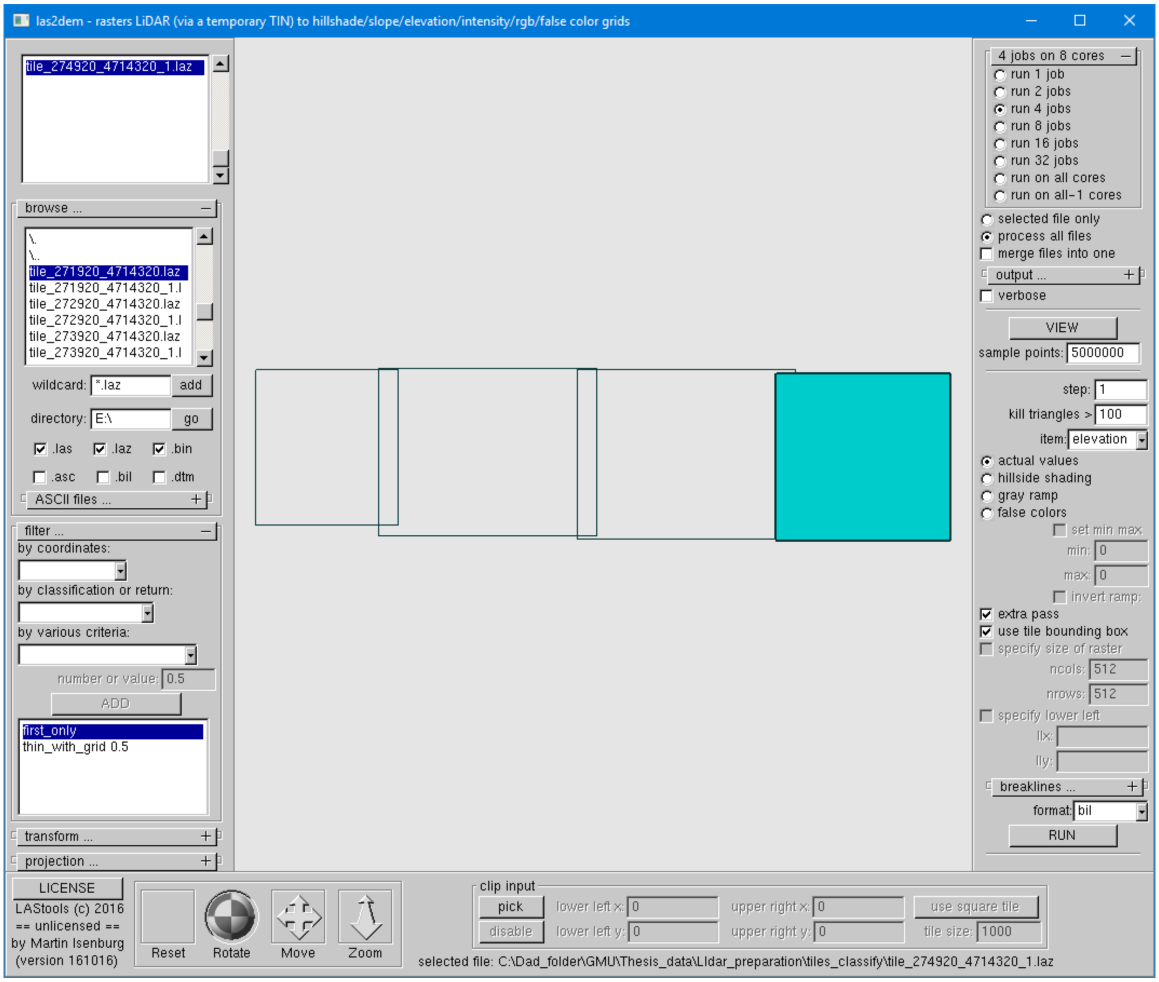


Figure 29: LAS2DEM DSM GUI

Keeping the first returns only creates a DSM.

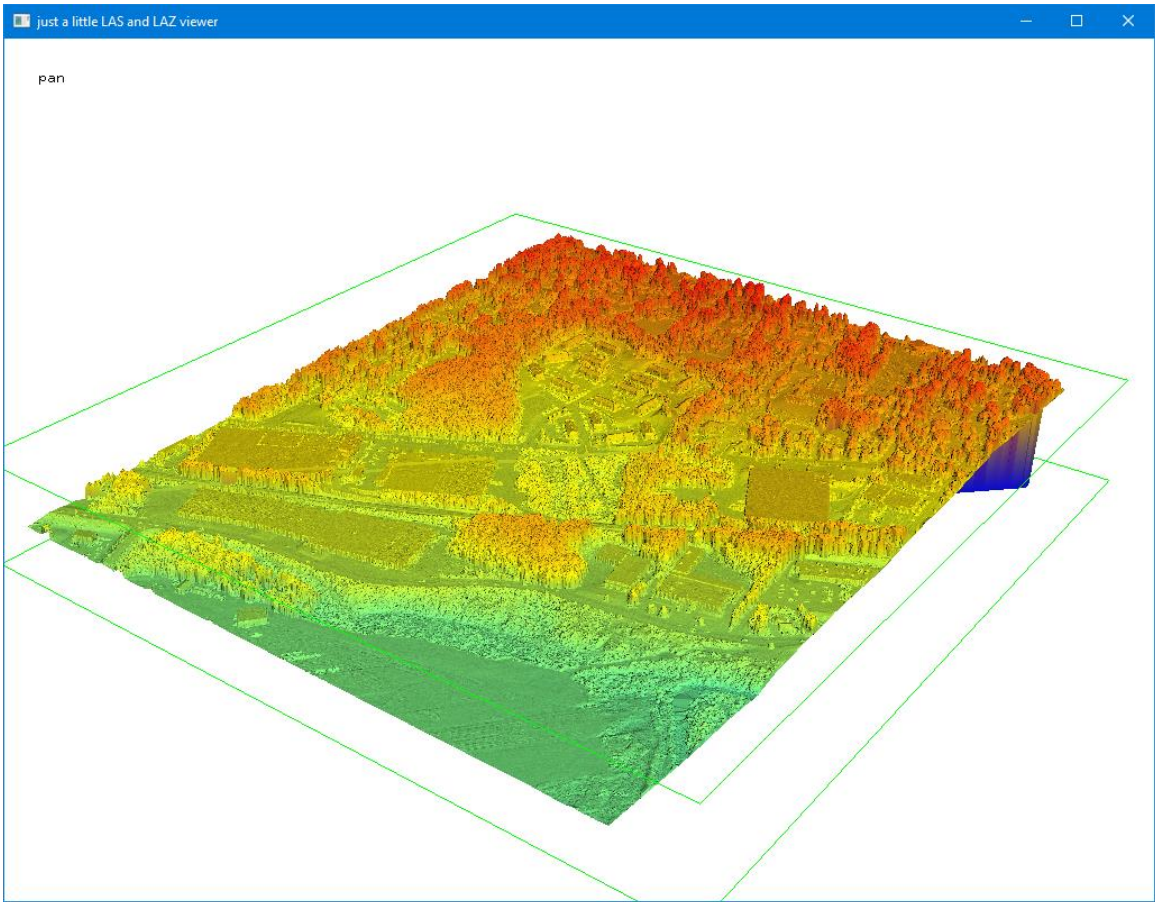


Figure 30: LAS2DEM DSM View

Section 3.3: Grid the lidar data

LASGrid is used to merge DEM tiles into one large DEM raster. This tool reads lidar from the LAS, LAZ, and ASCII format.

Section 3.4: Creating a Hillshade

For creating a hillshade of a DTM or DSM use the Blast2dem tool. The tool reads lidar points from the LAS or LAZ format. It can triangulate a seamless TIN and rasters the TIN into a DEM that can be tiled. You can create a PNG, TIF or JPG file to be used in ArcGIS or Google earth.

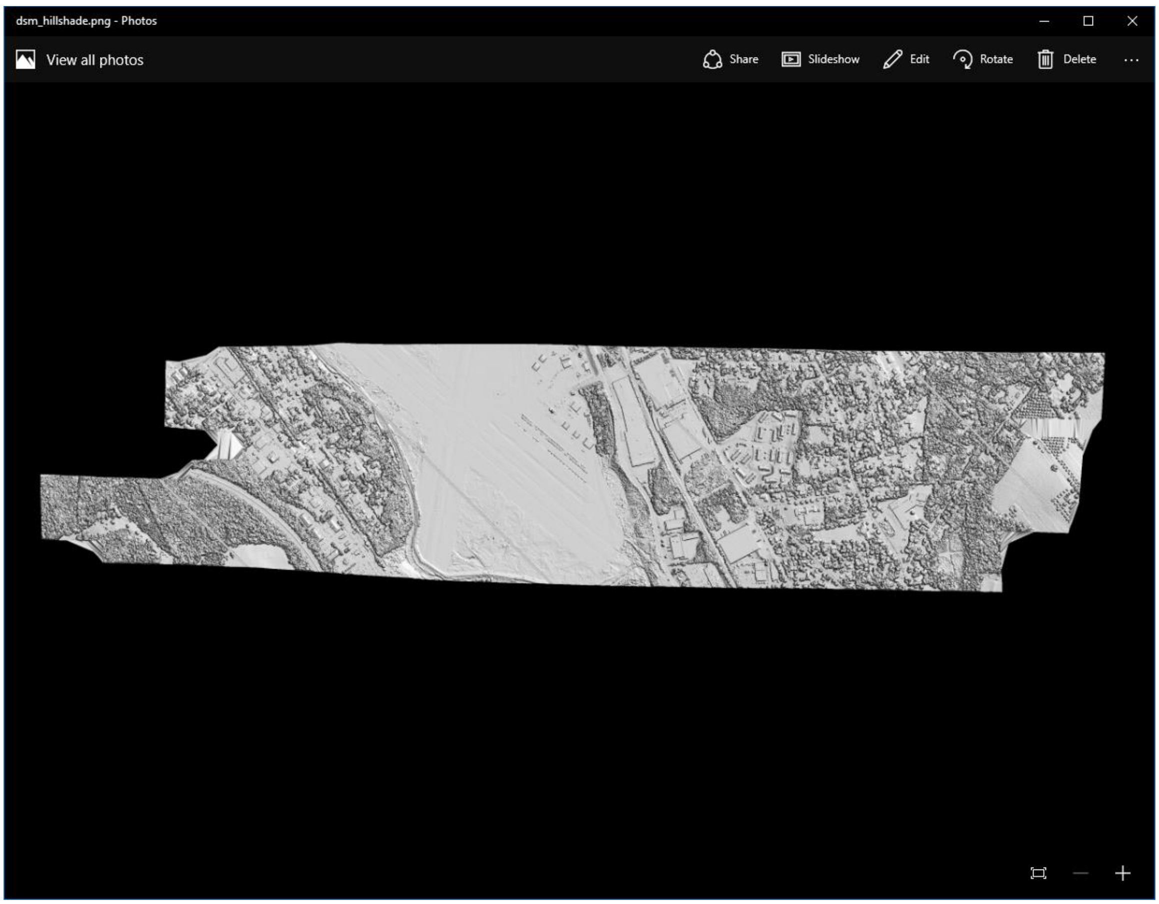


Figure 31: Hillshade DSM

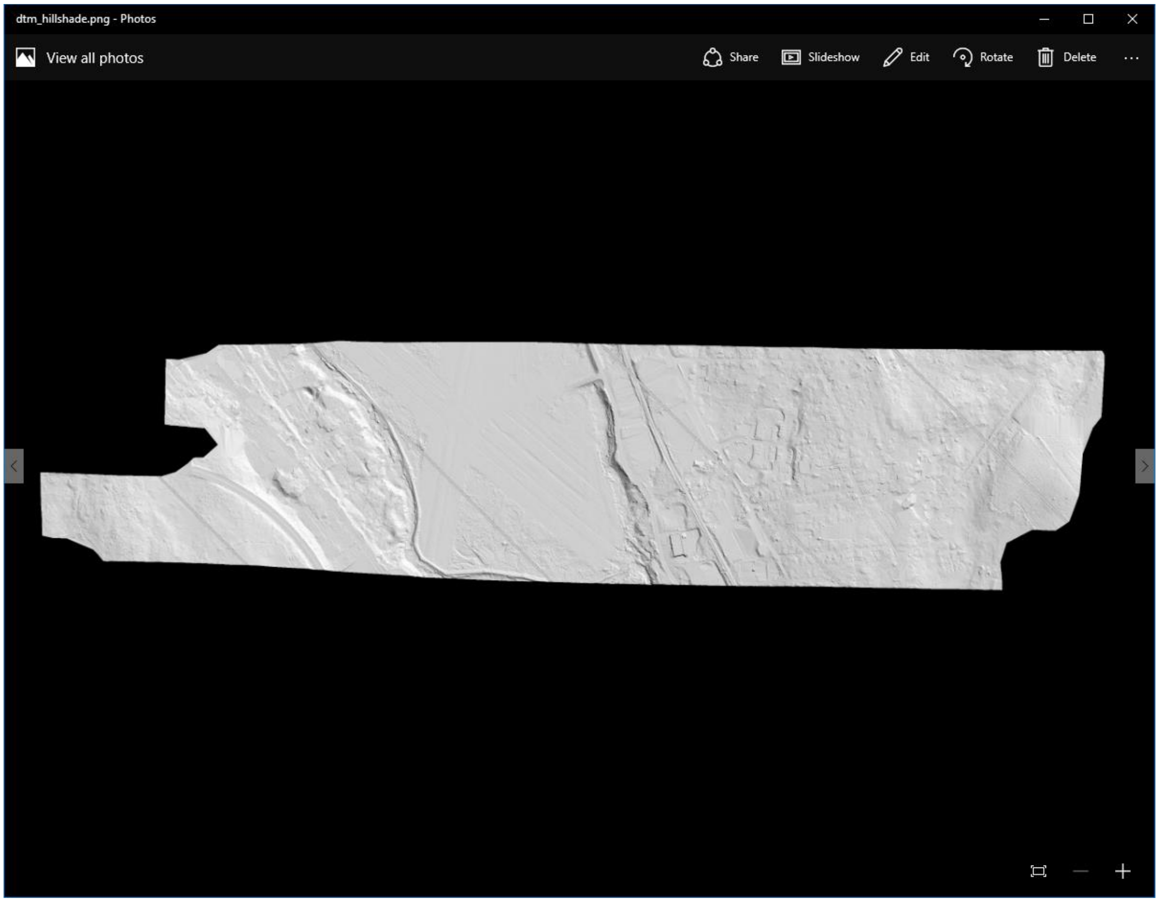


Figure 32: DTM Hillshade

Section 3.5: Creating Contours

Next we will use Blast2iso to create contour lines in a shapefile format. The tool can read lidar points in the LAS or LAZ format. It triangulates a seamless TIN and extracts contours at specified elevations from the TIN. The TIN can be smoothed and the contours simplified or cleaned. The first example will be for a one meter contour using the DTM as the source.

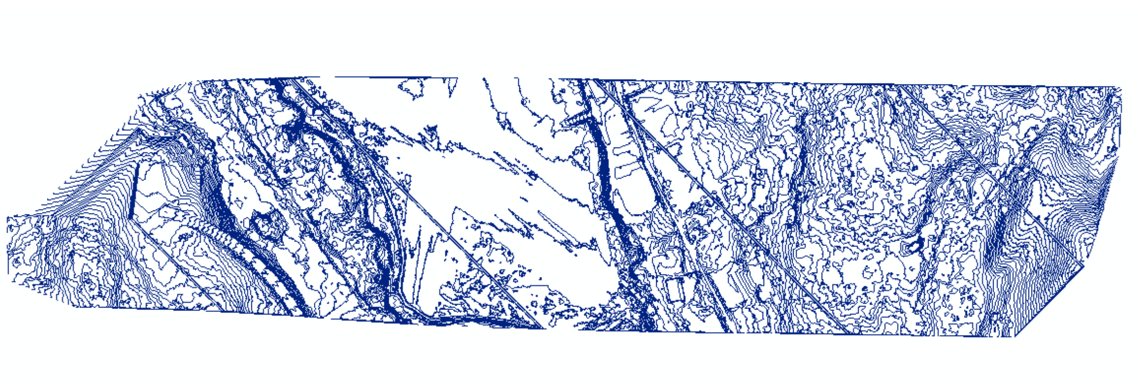


Figure 33: BLASt2ISO One meter DTM

Next, we will use Blast2iso to create contour lines in a shapefile format. This is three meter interval with DSM as the source.

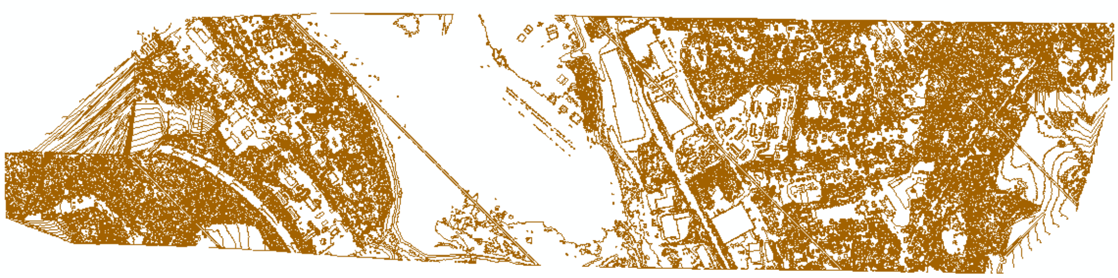


Figure 34: Blast2ISO three meter DSM

Section Four: Editing LAS files

Visually inspecting the point cloud and changing the attributes. You will notice some green points that are vegetation when it should be a building. There are some bluish spots that are unclassified and should be part of a building. With LASView, we can edit these points to the proper classification.

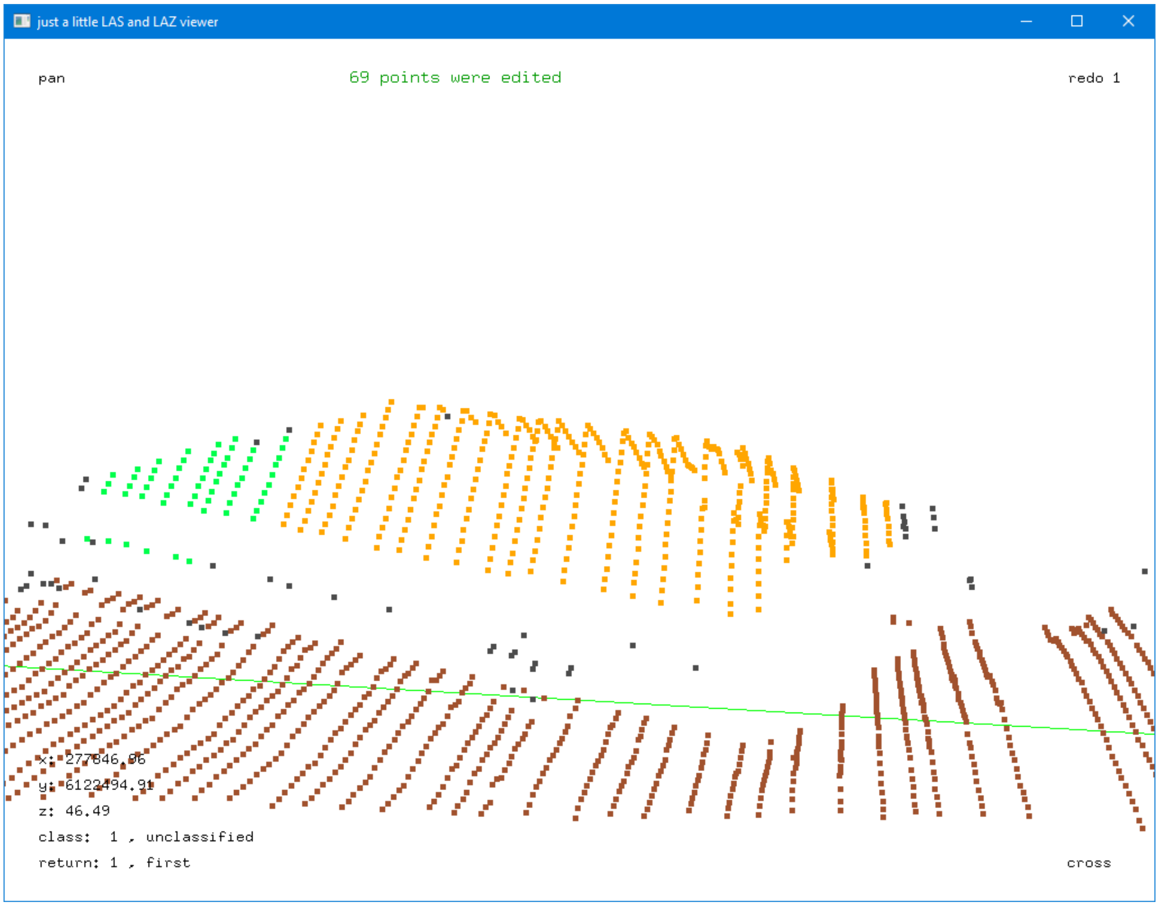


Figure 35: Initial View of building

In the editing mode, we can change the classification of the points. Now they are all orange for the building

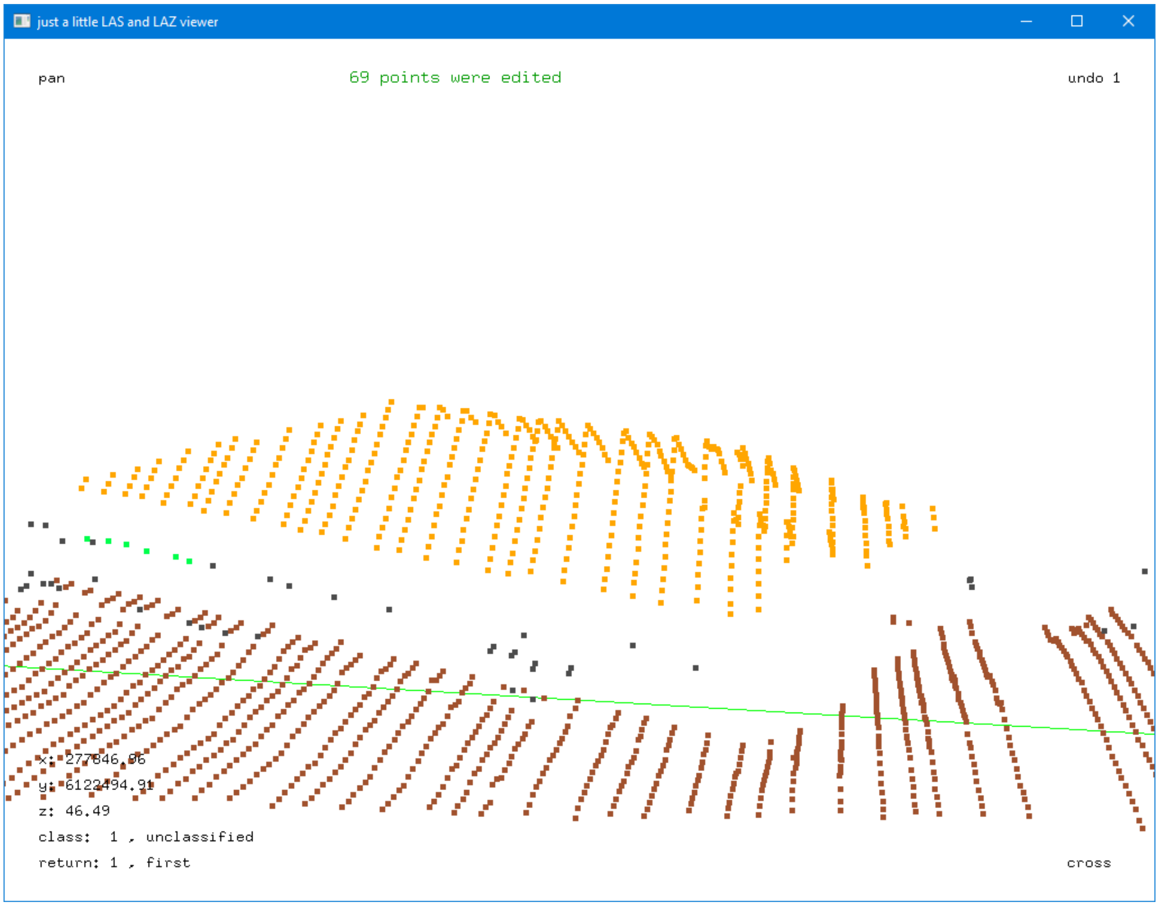


Figure 36: Building complete

Finally, we can triangulate the points according the classification of the lidar data and inspect the results for final review.

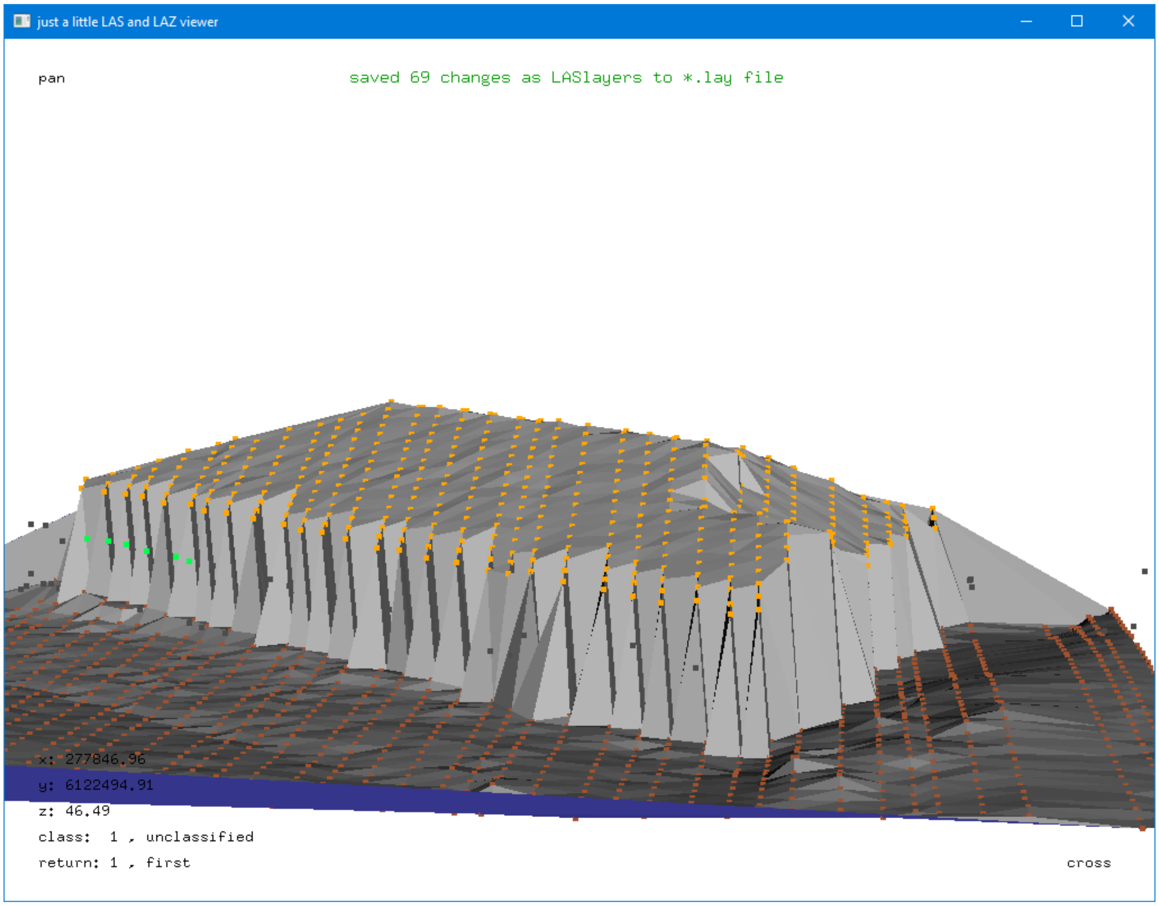


Figure 37: Triangulating the building

CHAPTER 6: COVERING LIDAR WITH IMAGERY (KAMENI ISLANDS)

Here is a collection of raw data that was made publicly available by Professor David Pyle on 14 August 2014. It is for the volcanic island New Kameni and a smaller island of Palea Kameni which are both part of the Santorini caldera in Greece. There are twelve flight lines for the Kameni islands that are provided in LAS format as well as simple ASCII files.

I ran the LAS info tool on strip one to look at the files. The Files are legacy LAS 1.0 files which need to be converted. The data was created in Julian day 137 in 2012. The scale factor is stored to 0.001 which is a millimeter. This is overkill for airborne lidar and would result in scanning noise which is misleading and a negative affect comparison.

LasInfoStrip1.txt - Notepad

File Edit Format View Help

```
  user ID                 'LeicaGeo'
  record ID               1002
  length after header     22
  description             'MissionInfo'
variable length header record 3 of 5:
  reserved                43707
  user ID                 'LeicaGeo'
  record ID               1005
  length after header     1536
  description             'IbrcInfo'
variable length header record 4 of 5:
  reserved                43707
  user ID                 'LeicaGeo'
  record ID               1003
  length after header     54
  description             'UserInputs'
variable length header record 5 of 5:
  reserved                43707
  user ID                 'LASF_Projection'
  record ID               34735
  length after header     56
  description             'Projection Info'
    GeoKeyDirectoryTag version 1.1.0 number of keys 6
      key 1024 tiff_tag_location 0 count 1 value_offset 1 - GTModelTypeGeoKey: ModelTypeProjected
      key 1025 tiff_tag_location 0 count 1 value_offset 2 - GTRasterTypeGeoKey: RasterPixelIsPoint
      key 3076 tiff_tag_location 0 count 1 value_offset 32635 - ProjLinearUnitsGeoKey: look-up for 32635 not implementec
      key 2052 tiff_tag_location 0 count 1 value_offset 9001 - GeogLinearUnitsGeoKey: Linear_Meter
      key 4096 tiff_tag_location 0 count 1 value_offset 5030 - VerticalCSTypeGeoKey: VertCS_WGS_84_ellipsoid
      key 4099 tiff_tag_location 0 count 1 value_offset 9001 - VerticalUnitsGeoKey: Linear_Meter
the header is followed by 2 user-defined bytes
reporting minimum and maximum for all LAS point record entries ...
  X           357429804  357955781
  Y            28763453   31303374
  Z               33156     233566
  intensity           0        255
  return_number       1          4
  number_of_returns   1          4
  edge_of_flight_line 0          1
  scan_direction_flag 0          1
  classification      1          7
  scan_angle_rank   -13         13
  user_data           0          0
  point_source_ID   255        255
  gps_time 294564.000008 294599.194018
number of first returns:        2079412
number of intermediate returns: 13
number of last returns:         2079412
number of single returns:       2078643
overview over number of returns of given pulse: 2078643 1514 33 4 0 0 0
histogram of classification of points:
         2080142  unclassified (1)
              52  noise (7)
```

Figure 38: LASinfo of Kameni islands

First we will look at all twelve lidar strips in LASView. You can clearly see the two islands in the view that are of a lighter blue color. The red pixels are clouds in the scanned area with some voided areas that appear white in the background.

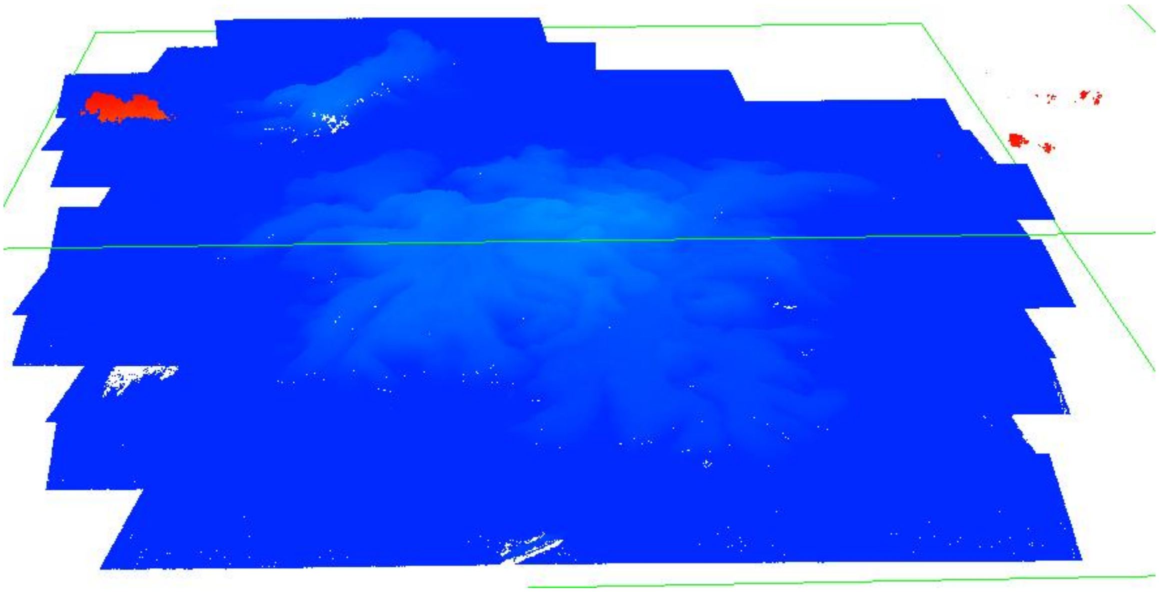


Figure 39: Clear view of islands

If you change the angle, you can obviously see the cloud features that got returned in red pixels.

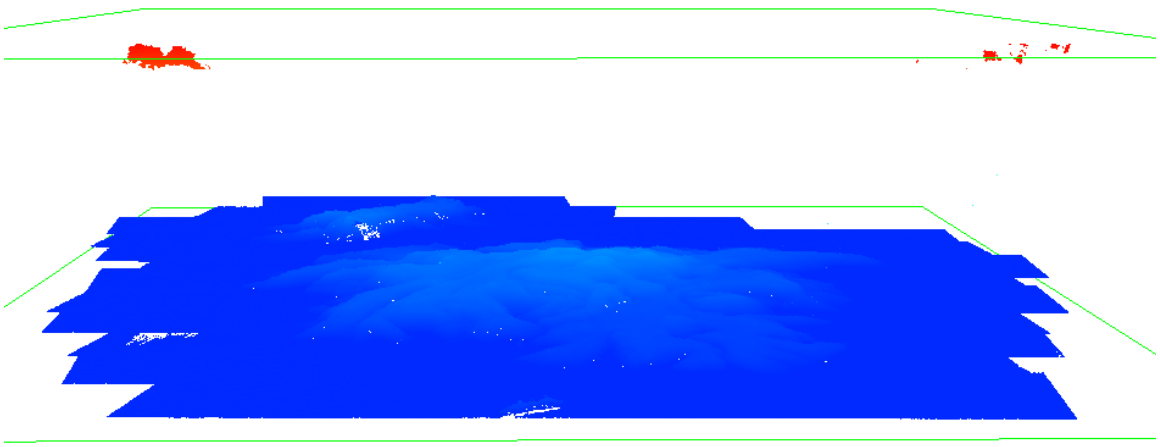


Figure 40: Clear view of clouds in red

Looking at another view at sea level and zooming in you can clearly see a cruise ship that was in the area of interest at the time it was scanned.

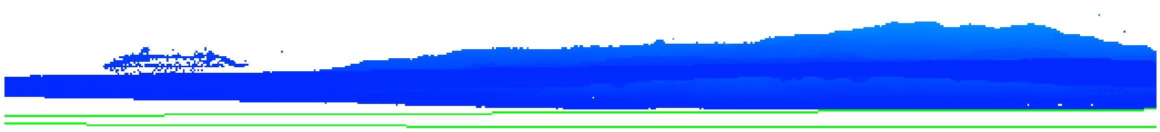


Figure 41: Clear view of cruise ship in image

Looking at the ortho photo imagery you can easily see the islands are volcanic with little vegetation.

Figure 42: Ortho photo imagery

Now we will view the intensity of the lidar data. The flight lines and different angles are easily seen in this scanned set.

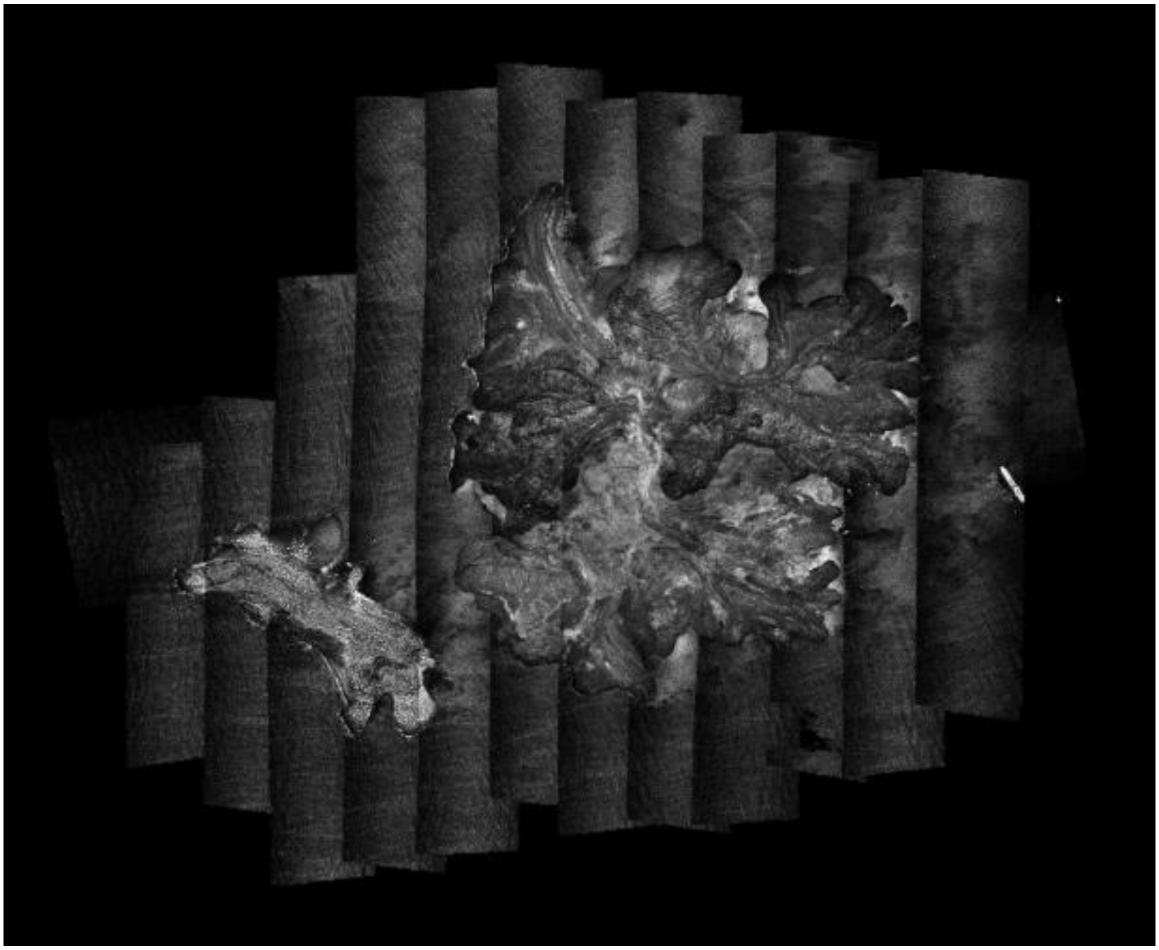
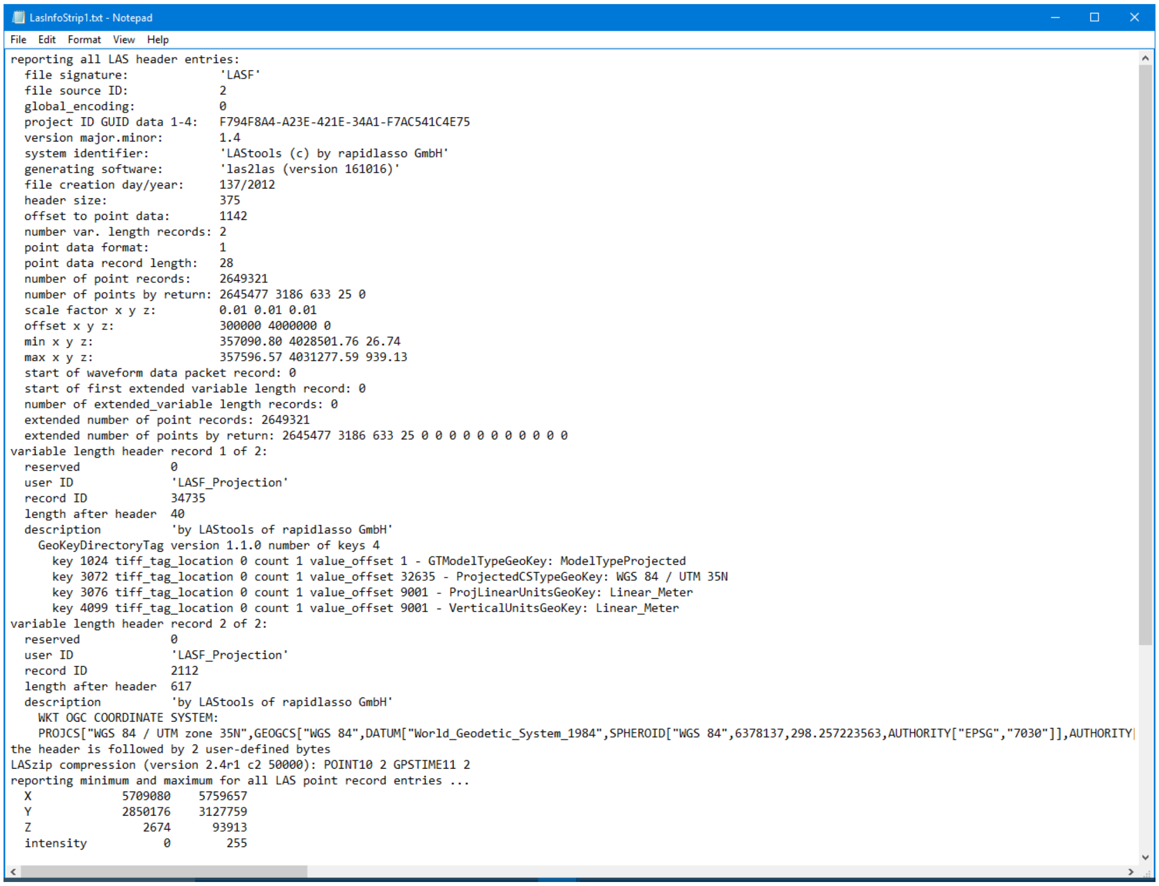


Figure 43: Intensity of Lidar

After viewing the twelve lidar strips, we will adjust the raw lidar to make it more efficient and useful. We will use LAS2LAS to do the following items. I switched the LAS 1.0 to the newer version of LAS 1.4, removed all the VLRs, set the horizontal projection to EPSG code 32635 and the vertical datum to WGS84 and converted it to UTM 35 North, WGS 84, and rescaled the lidar from one millimeter to one centimeter lidar data. By rescaling from every millimeter to a centimeter and converting to LAZ 1.4 instead of LAS file we saved a considerable amount of space. 3.1 GB to 106 MB.



```
reporting all LAS header entries:
  file signature:             'LASF'
  file source ID:             2
  global_encoding:            0
  project ID GUID data 1-4:   F794F8A4-A23E-421E-34A1-F7AC541C4E75
  version major.minor:        1.4
  system identifier:          'LAStools (c) by rapidlasso GmbH'
  generating software:        'las2las (version 161016)'
  file creation day/year:     137/2012
  header size:                375
  offset to point data:       1142
  number var. length records: 2
  point data format:          1
  point data record length:   28
  number of point records:    2649321
  number of points by return: 2645477 3186 633 25 0
  scale factor x y z:         0.01 0.01 0.01
  offset x y z:               300000 4000000 0
  min x y z:                  357090.80 4028501.76 26.74
  max x y z:                  357596.57 4031277.59 939.13
  start of waveform data packet record: 0
  start of first extended variable length record: 0
  number of extended_variable length records: 0
  extended number of point records: 2649321
  extended number of points by return: 2645477 3186 633 25 0 0 0 0 0 0 0 0 0 0 0
variable length header record 1 of 2:
  reserved             0
  user ID              'LASF_Projection'
  record ID            34735
  length after header  40
  description          'by LAStools of rapidlasso GmbH'
    GeoKeyDirectoryTag version 1.1.0 number of keys 4
      key 1024 tiff_tag_location 0 count 1 value_offset 1 - GTModelTypeGeoKey: ModelTypeProjected
      key 3072 tiff_tag_location 0 count 1 value_offset 32635 - ProjectedCSTypeGeoKey: WGS 84 / UTM 35N
      key 3076 tiff_tag_location 0 count 1 value_offset 9001 - ProjLinearUnitsGeoKey: Linear_Meter
      key 4099 tiff_tag_location 0 count 1 value_offset 9001 - VerticalUnitsGeoKey: Linear_Meter
variable length header record 2 of 2:
  reserved             0
  user ID              'LASF_Projection'
  record ID            2112
  length after header  617
  description          'by LAStools of rapidlasso GmbH'
    WKT OGC COORDINATE SYSTEM:
    PROJCS["WGS 84 / UTM zone 35N",GEOGCS["WGS 84",DATUM["World_Geodetic_System_1984",SPHEROID["WGS 84",6378137,298.257223563,AUTHORITY["EPSG","7030"]],AUTHORITY
the header is followed by 2 user-defined bytes
LASzip compression (version 2.4r1 c2 50000): POINT10 2 GPSTIME11 2
reporting minimum and maximum for all LAS point record entries ...
  X             5709080    5759657
  Y             2850176    3127759
  Z                2674      93913
  intensity           0        255
```

Figure 44: LASinfo of Kameni Islands after conversion

To create a nice finished product, I used LAS color to overlap imagery on top of the Lidar points. LASColor computes which pixel a LAS point corresponds with the RGB value of the ortho photo accordingly.

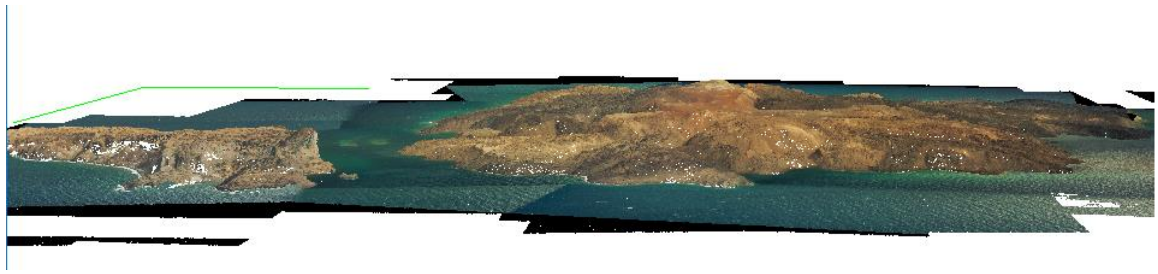


Figure 45: Air photo imagery laid over Lidar data

CHAPTER 7: POTOMAC RIVER EXPERIMENT

For Airborne Lidar, I used a local area to the DC area; Survey Parts of Potomac and Susquehanna Rivers. I choose this area because I am somewhat familiar with it and I know it has a bridge, C&O canal, roads, and buildings to reference the lidar with. With the restriction of processing LAStools on a free version, with larger datasets the software will place white lines to distort the display to deter large dataset processing for free. I had to decrease the size of the project to try to avoid. I choose to concentrate on the Carderock naval warfare center.

Section One: Open Topography (Lidar)

The Lidar was downloaded from Open Topography. The Open Topography website has three types of lidar; airborne lidar, terrestrial Laser scanner, and structure from Motion/ Photogrammetry. I cut a portion of the lidar dataset that was available was from the NCALM Project. PI: Paul Bierman, University of Vermont. The survey area consisted of two polygons: 1) over a portion of the Potomac River in Washington D.C. enclosing 60 square km; and 2) over a portion of the Susquehanna River in Pennsylvania enclosing 23 square km. The Susquehanna survey took place on January 9, 2005 and the Potomac survey took place on January 11, 2005.

Horiz. Coordinates: UTM z18 N NAD83 (CORS96) [EPSG: 26918]

Vertical Coordinates: NAVD88 (Geoid 03) [EPSG: 5703]

Point Density: 1.37pts/m^2

Area: 85.00km^2

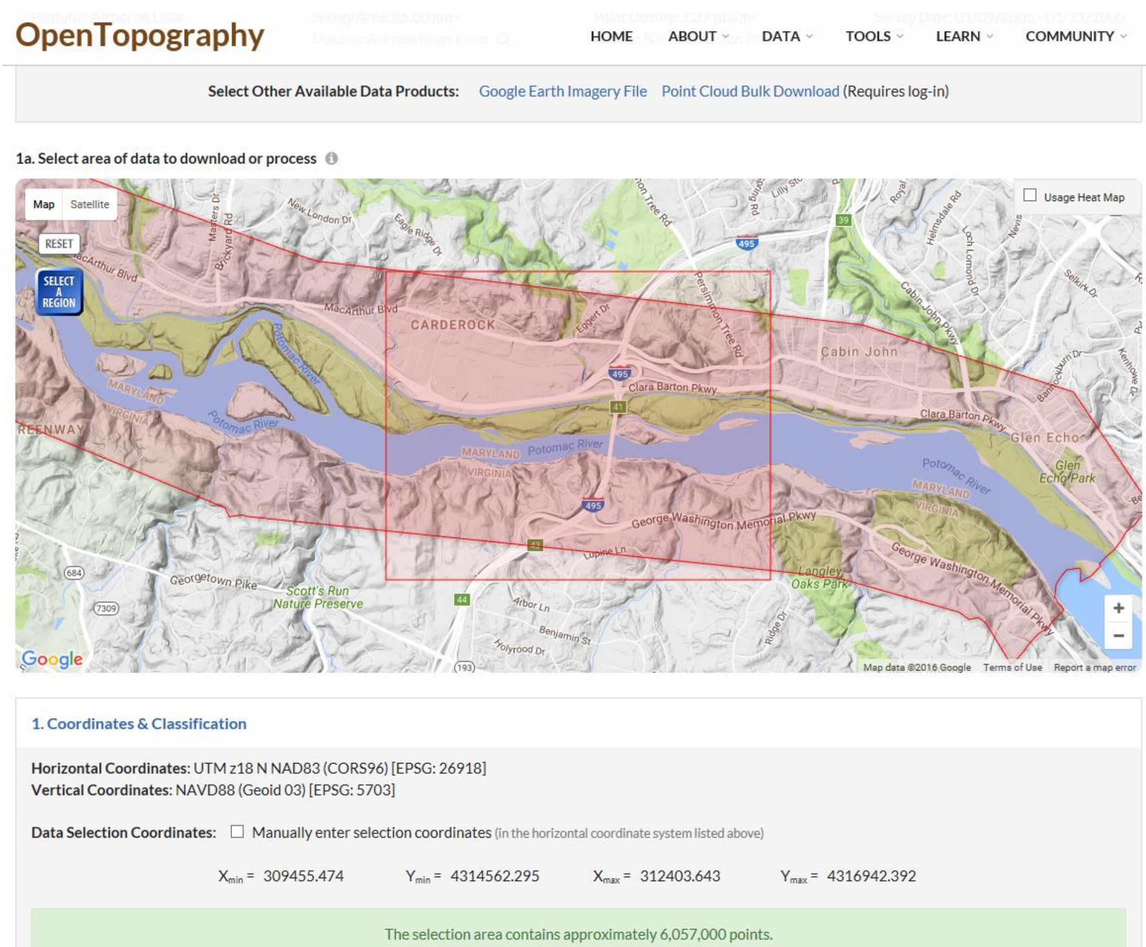


Figure 46: Open Topography website for the Area of Interest

Downloaded point cloud data in LAS, LAZ, DEM results, and derivative products: Hillshade & Slope Products (TIN). There are a few options for Point Cloud Data to download; LAS, LAZ or ASCII format. The LAS file format is a public file format for the interchange of 3-dimensional lidar point cloud data. This binary file format is an alternative to proprietary systems or a generic ASCII file interchange system and is compatible with many commercial and open source software packages. LAZ is the next option. It is a LASzip (.LAZ) is a lossless compression for binary LAS format lidar point cloud data. LAZ files are typically 10-20% of their uncompressed LAS equivalent and are therefore easier to download and store. LAZ files are produced with the open source LASzip library: http://LASzip.org/. Selection of this option returns the lidar point cloud for the area selected above as an ASCII file (comma delimited, one point per line).

Section Two: USGS Earth Explorer (Imagery and SRTM data)

USGS Earth Explorer provides a large range of different datasets and is the prime source of Geographic Information system data for the system. The data can be downloaded free of purchase. Imagery and SRTM data was downloaded from USGS Earth Explorer for the area of Interest that compliments the lidar that was downloaded.

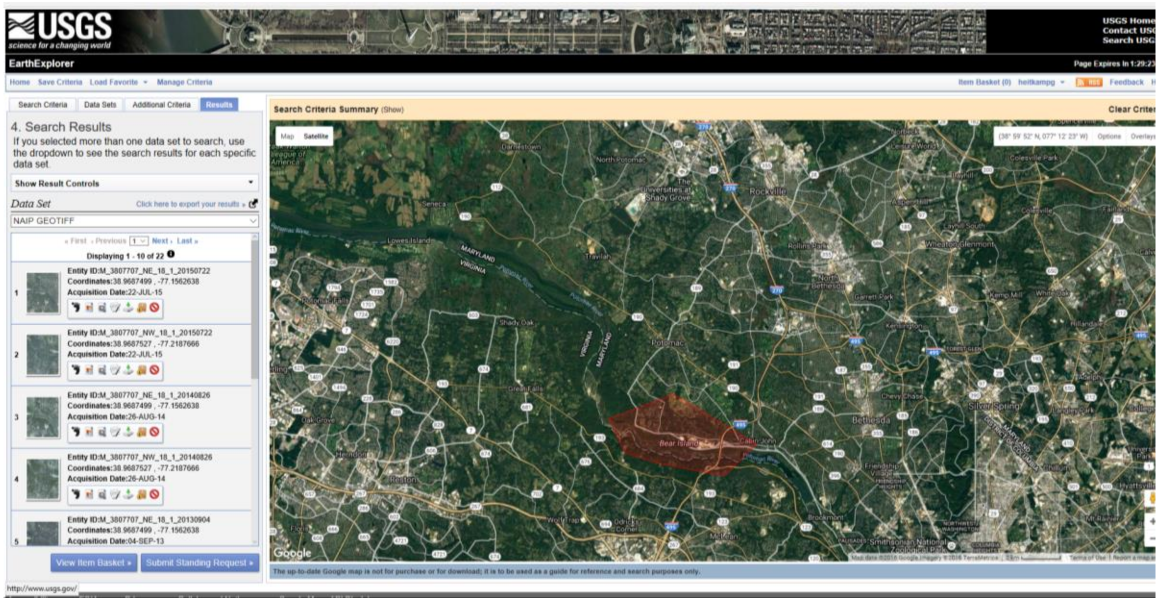


Figure 47: USGS Earth Explorer

Section Three: National Geodetic Survey Data Explorer

The National Geodetic Survey Data Explorer contains a dataset that has Survey control point's data throughout the United States. Survey control points were downloaded for the area of Interest.

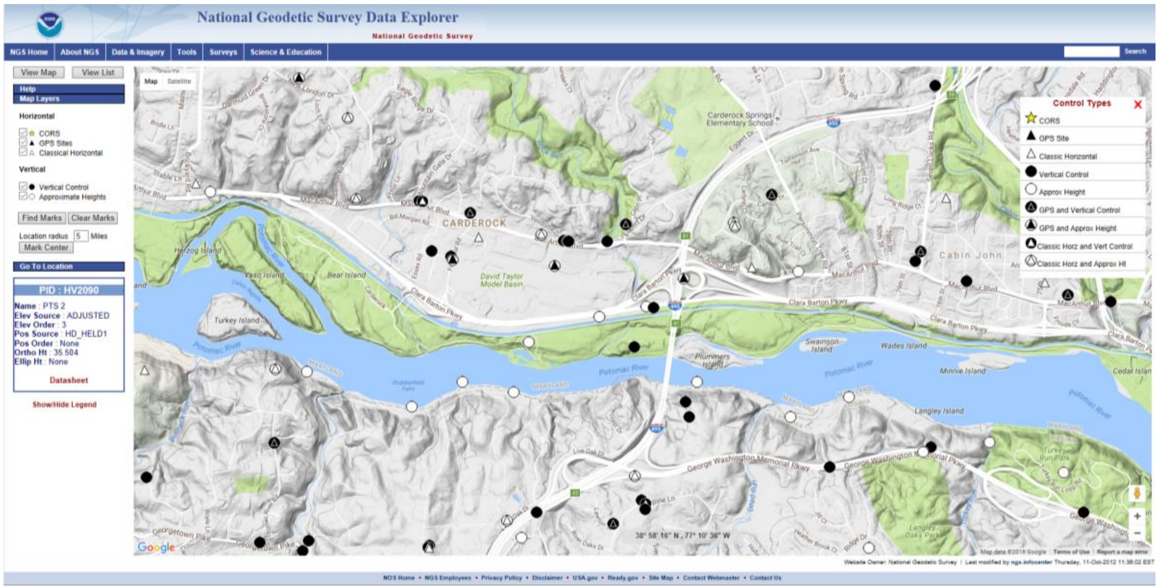


Figure 48: National Geodetic Survey Data Explorer

Section Four: Processing Lidar data

To comply with LAStools unlicensed limits, a smaller section of the lidar was downloaded. The initial download was over seven million points and the newer section was 1,460,296 points instead. Below is two screenshots of the smaller area of interest.

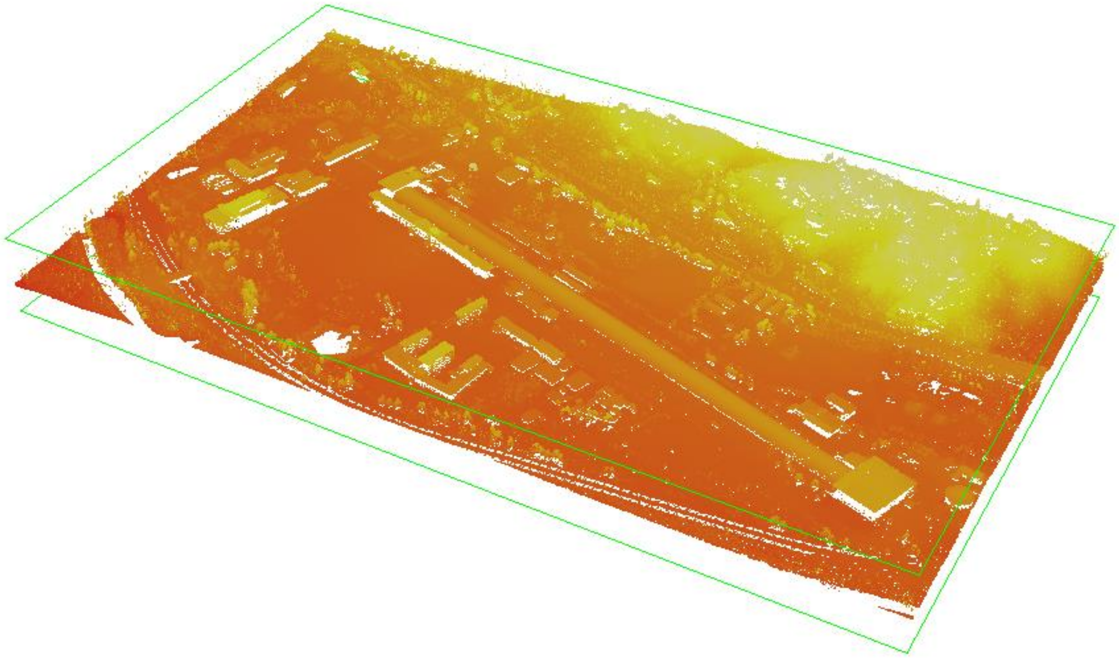


Figure 49: LASview of Warfare center last return (Surface View)

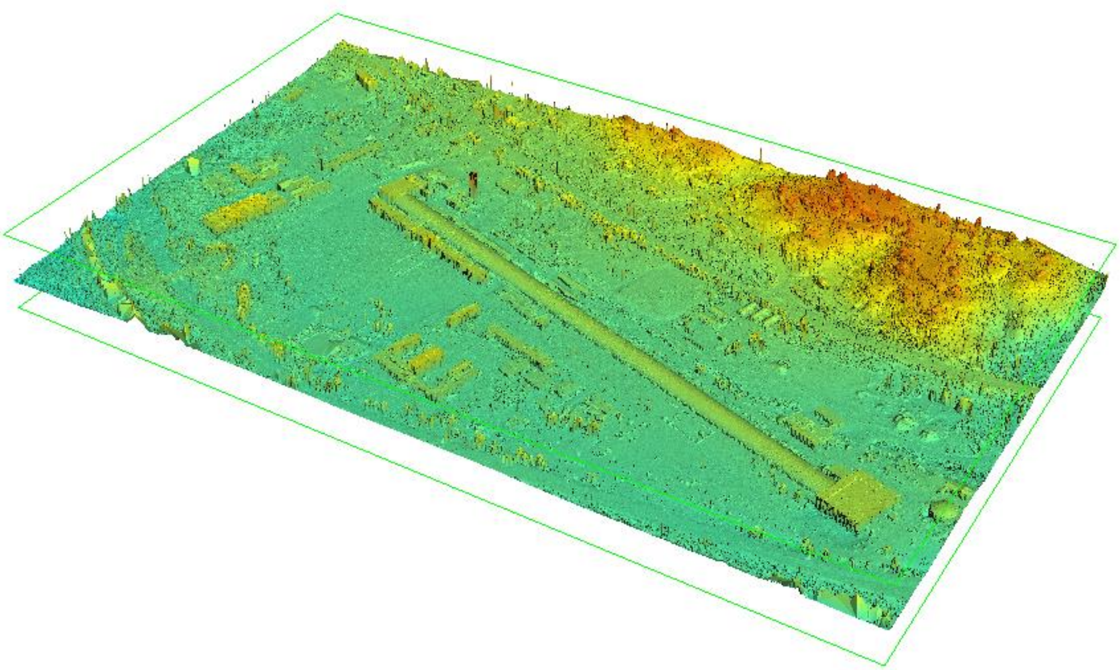
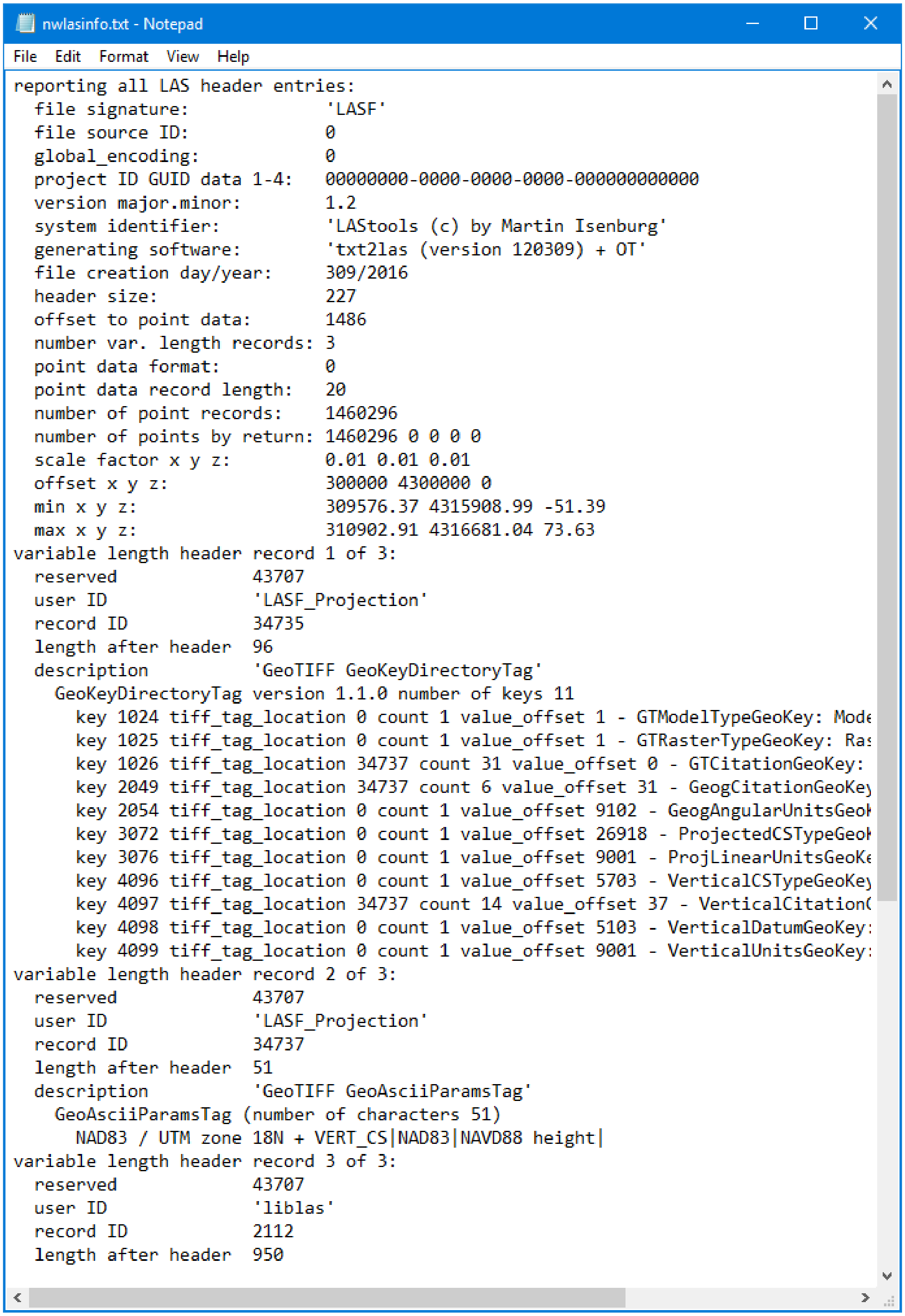


Figure 50: LASview Warfare center all return

After viewing the LAS files in LASview, we will use LASinfo to display the information about the lidar data.



```
reporting all LAS header entries:
  file signature:             'LASF'
  file source ID:             0
  global_encoding:            0
  project ID GUID data 1-4:   00000000-0000-0000-0000-000000000000
  version major.minor:        1.2
  system identifier:          'LAStools (c) by Martin Isenburg'
  generating software:        'txt2las (version 120309) + OT'
  file creation day/year:     309/2016
  header size:                227
  offset to point data:       1486
  number var. length records: 3
  point data format:          0
  point data record length:   20
  number of point records:    1460296
  number of points by return: 1460296 0 0 0 0
  scale factor x y z:         0.01 0.01 0.01
  offset x y z:               300000 4300000 0
  min x y z:                  309576.37 4315908.99 -51.39
  max x y z:                  310902.91 4316681.04 73.63
variable length header record 1 of 3:
  reserved             43707
  user ID              'LASF_Projection'
  record ID            34735
  length after header  96
  description          'GeoTIFF GeoKeyDirectoryTag'
    GeoKeyDirectoryTag version 1.1.0 number of keys 11
      key 1024 tiff_tag_location 0 count 1 value_offset 1 - GTModelTypeGeoKey: Mode
      key 1025 tiff_tag_location 0 count 1 value_offset 1 - GTRasterTypeGeoKey: Ras
      key 1026 tiff_tag_location 34737 count 31 value_offset 0 - GTCitationGeoKey:
      key 2049 tiff_tag_location 34737 count 6 value_offset 31 - GeogCitationGeoKey
      key 2054 tiff_tag_location 0 count 1 value_offset 9102 - GeogAngularUnitsGeoK
      key 3072 tiff_tag_location 0 count 1 value_offset 26918 - ProjectedCSTypeGeoK
      key 3076 tiff_tag_location 0 count 1 value_offset 9001 - ProjLinearUnitsGeoKe
      key 4096 tiff_tag_location 0 count 1 value_offset 5703 - VerticalCSTypeGeoKey
      key 4097 tiff_tag_location 34737 count 14 value_offset 37 - VerticalCitationG
      key 4098 tiff_tag_location 0 count 1 value_offset 5103 - VerticalDatumGeoKey:
      key 4099 tiff_tag_location 0 count 1 value_offset 9001 - VerticalUnitsGeoKey:
variable length header record 2 of 3:
  reserved             43707
  user ID              'LASF_Projection'
  record ID            34737
  length after header  51
  description          'GeoTIFF GeoAsciiParamsTag'
    GeoAsciiParamsTag (number of characters 51)
      NAD83 / UTM zone 18N + VERT_CS|NAD83|NAVD88 height|
variable length header record 3 of 3:
  reserved             43707
  user ID              'liblas'
  record ID            2112
  length after header  950
```

Figure 51: LASinfo of the lidar data for the warfare center

LASControl will read lidar data in LAS, LAZ, and ASCII format and triangulates the relevant points into a TIN. Now, we will compare the Lidar elevation with a set of 18 exactly known control points pulled from National Geodetic Survey Data explorer. The data had to be converted from Latitude and Longitude to Northing and Eastings and then compared with the Lidar data. We will use LAS Control to check the data. The first graphic is the LAS Control GUI. The red dots are the survey control points. The second graphic is the text file that is calculated with the errors and the third graphic is the view of the area in LAS View with red dots as the survey control points. You can see how the red dots line up accurately with the lidar data.

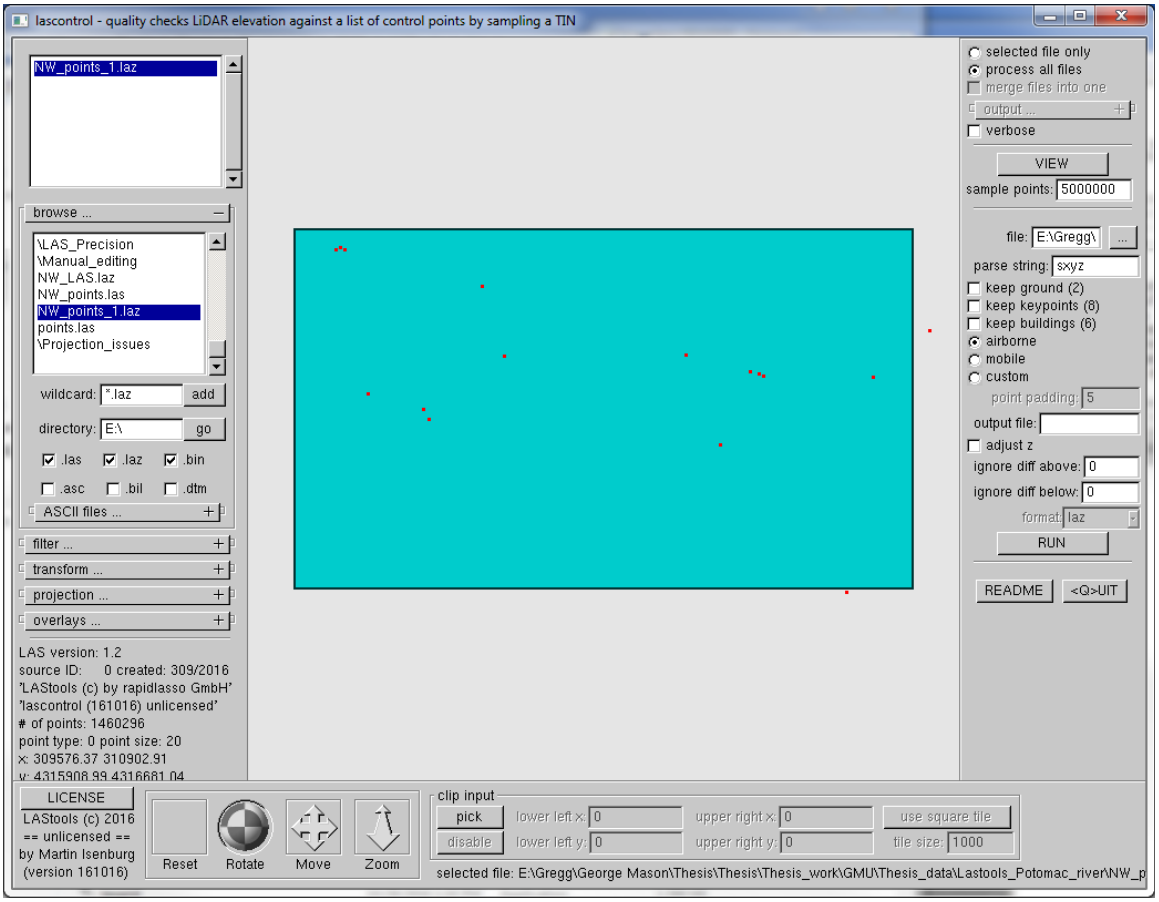


Figure 52: LAS Control GUI of warfare center

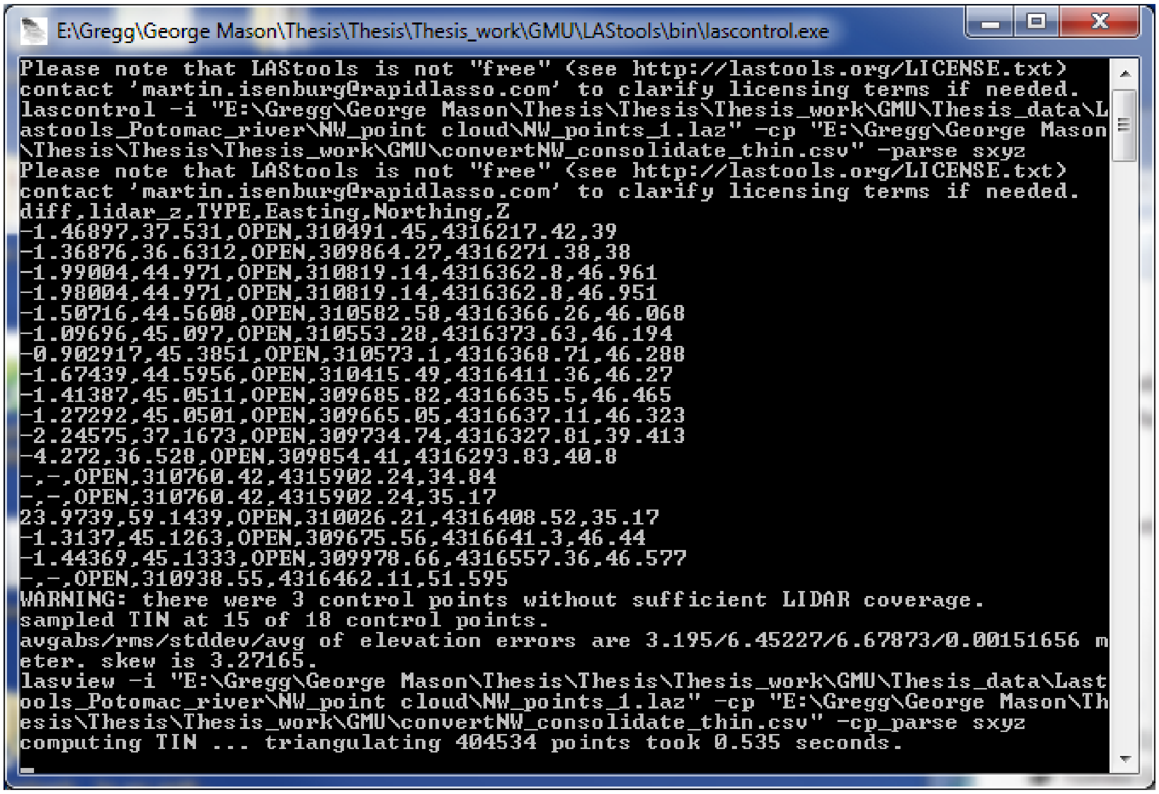


Figure 53: LAS Control read out of warfare center

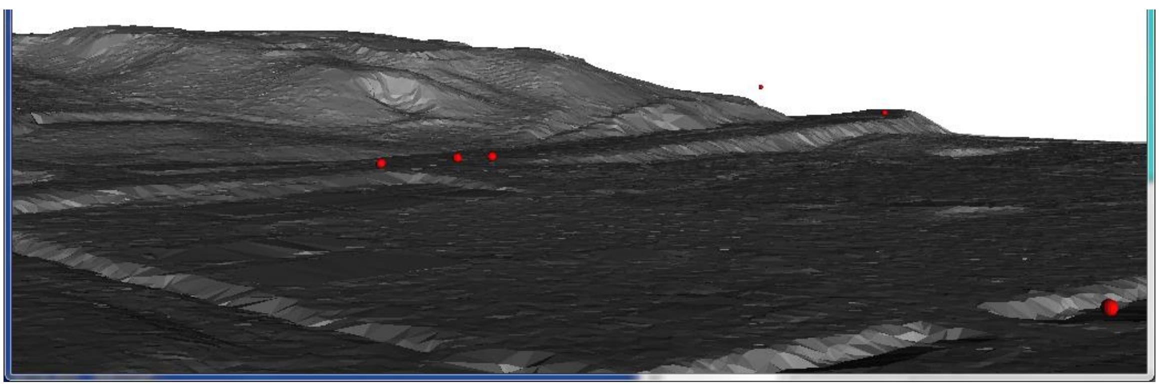


Figure 54: LAS View of the control for warfare center red dots are the survey control points

Next we will use LAS ground. LAS ground is a tool for bar-earth extraction. It classifies Lidar points into ground points, class = 2, and non-ground points; class =1. This tool is designed to work well in natural environments such as mountains, forests, fields, hills, and other terrain with few man-made features. This tool also produces excellent results for town or cities but buildings larger than the step size can be problematic. The default step is 5 meters for forest and mountains. For towns and flat terrain, the step increases to 10 meters. For larger cities or warehouses the step increases again to 25 meters. For large metropolitan areas, the step increase to 50 meters. By default, this tool only considers the last return.

I worked with two separate ground specifications. The first was with city and warehouses using the setting of ultra. The main warehouse in the middle was not completely picked up as a building. Some of the building was considered ground by the program. The second was with metropolis and a setting of hyper. You can see that it determined the main warehouse was all building instead of partial ground.

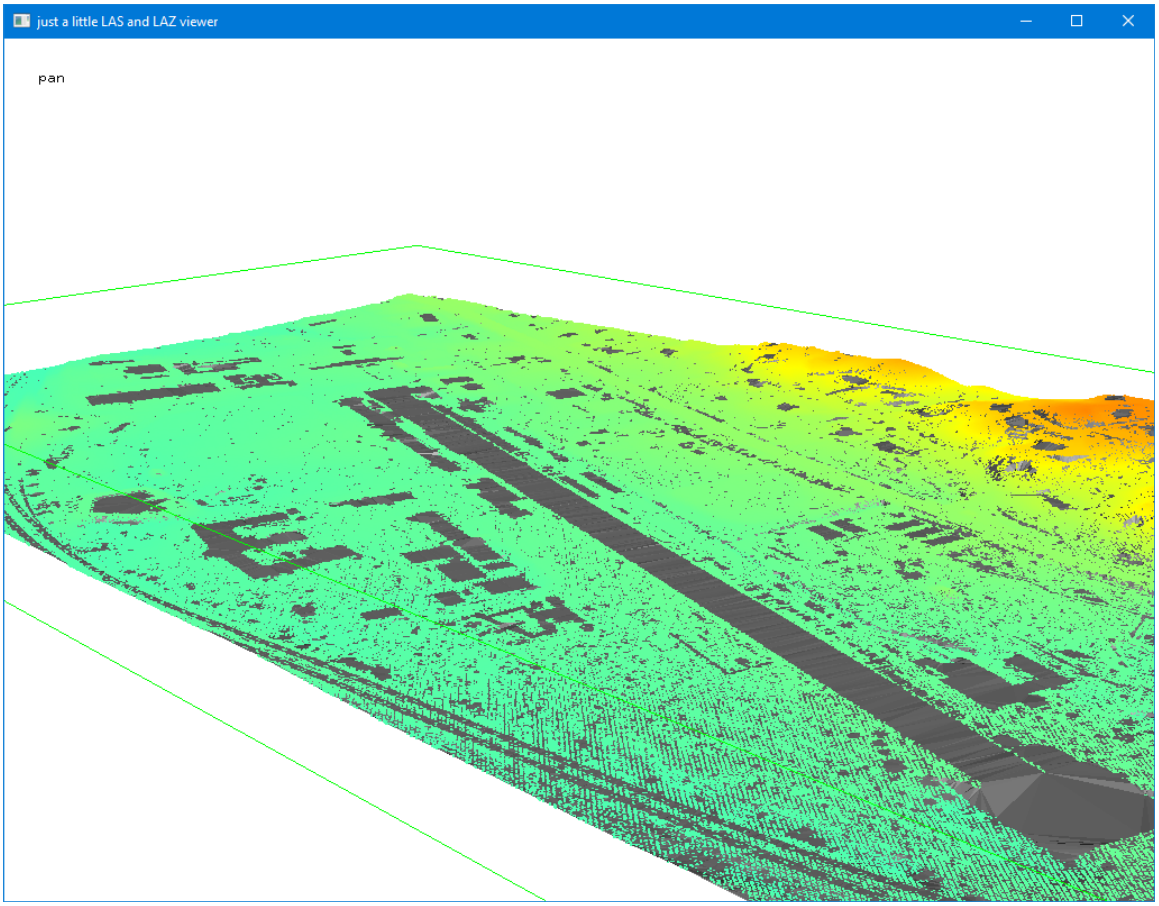


Figure 55: LASGround image of warfare center

After running LASGround, we will then run the tool LASHeight. We will remove dirt points below the ground and air points far above the ground. The tool will compute the vertical distance for each point to the triangulation of the ground points. We will use these heights in the future for finding vegetation and buildings. Using the points classified as ground to construct a TIN and then calculate the heights of all other points in respect to this ground surface. We will remove all the points that are 2 meters below and 30 meters above ground surface.

Next we will run LASClassify. The process is not 100 percent correct, it does identify most of the features by man-made or vegetation above 2 meters. The first screen shot is the lidar classified and the second shot is the imagery. You can see they are very familiar to one another just at different angles.

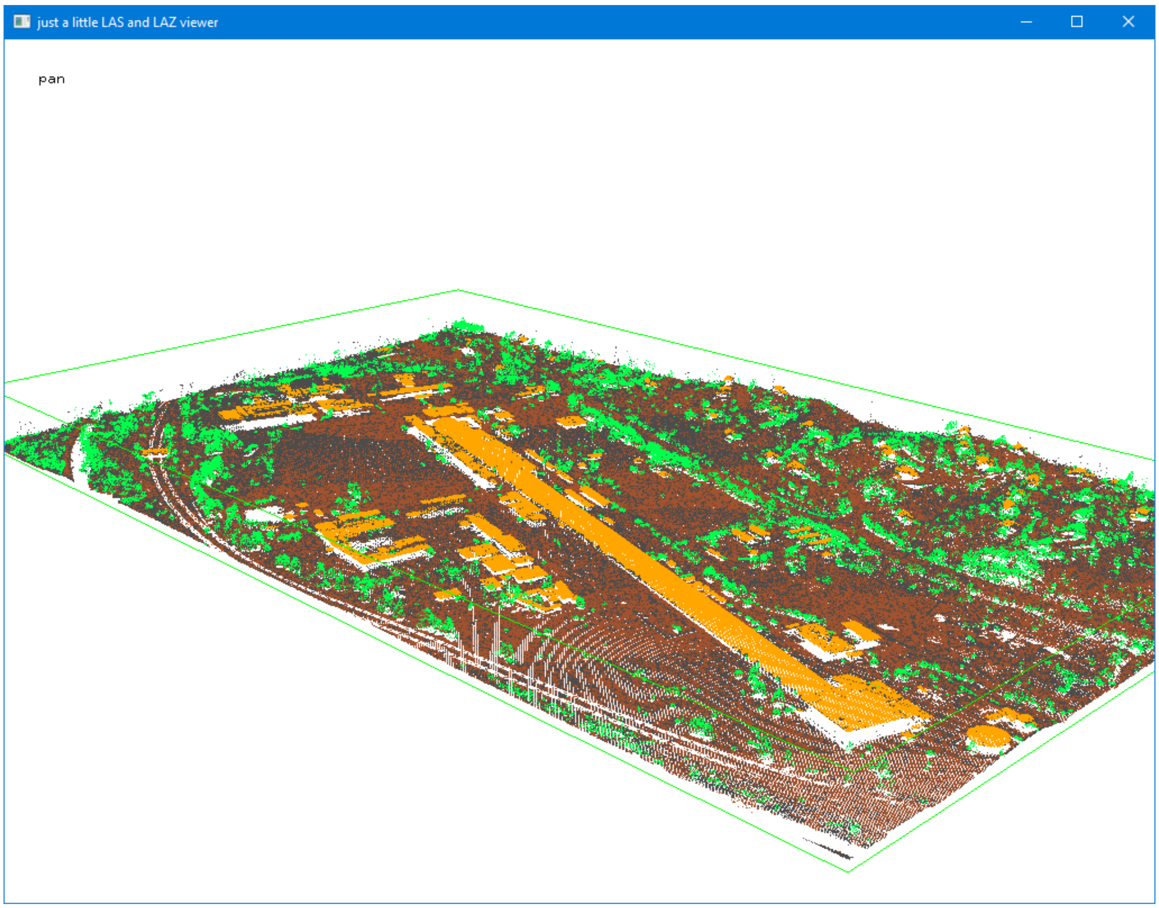
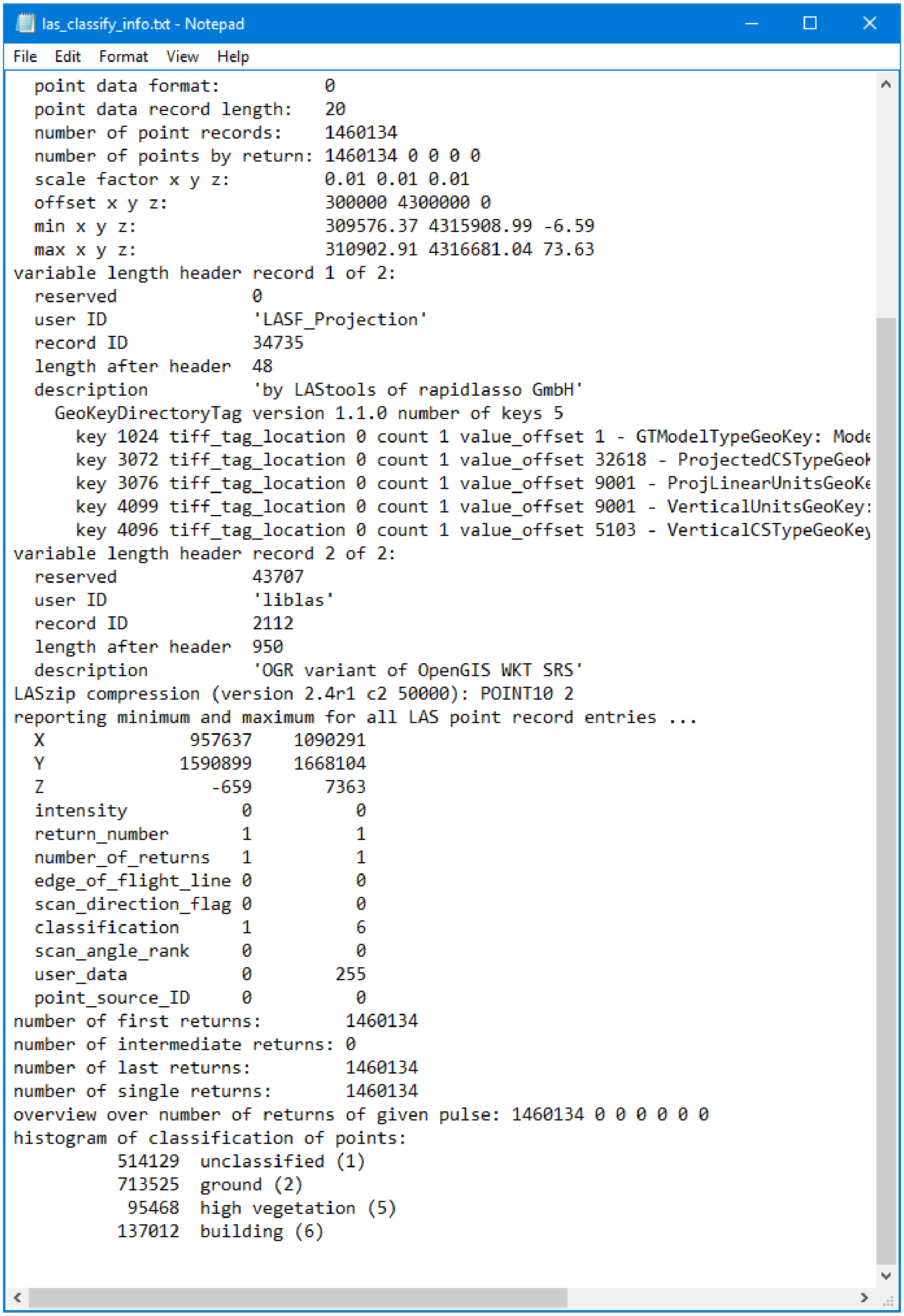


Figure 56: View of classified lidar for warfare center

Figure 57: View of imagery over the warfare center

We will then run LASInfo on the lidar data and compute the density and the number of classified returns.


las_classify_info.txt - Notepad

File Edit Format View Help

```
  point data format:          0
  point data record length:   20
  number of point records:    1460134
  number of points by return: 1460134 0 0 0 0
  scale factor x y z:         0.01 0.01 0.01
  offset x y z:               300000 4300000 0
  min x y z:                  309576.37 4315908.99 -6.59
  max x y z:                  310902.91 4316681.04 73.63
variable length header record 1 of 2:
  reserved             0
  user ID              'LASF_Projection'
  record ID            34735
  length after header  48
  description          'by LAStools of rapidlasso GmbH'
    GeoKeyDirectoryTag version 1.1.0 number of keys 5
      key 1024 tiff_tag_location 0 count 1 value_offset 1 - GTModelTypeGeoKey: Mode
      key 3072 tiff_tag_location 0 count 1 value_offset 32618 - ProjectedCSTypeGeoK
      key 3076 tiff_tag_location 0 count 1 value_offset 9001 - ProjLinearUnitsGeoKe
      key 4099 tiff_tag_location 0 count 1 value_offset 9001 - VerticalUnitsGeoKey:
      key 4096 tiff_tag_location 0 count 1 value_offset 5103 - VerticalCSTypeGeoKey
variable length header record 2 of 2:
  reserved             43707
  user ID              'liblas'
  record ID            2112
  length after header  950
  description          'OGR variant of OpenGIS WKT SRS'
LASzip compression (version 2.4r1 c2 50000): POINT10 2
reporting minimum and maximum for all LAS point record entries ...
  X              957637     1090291
  Y             1590899     1668104
  Z                -659        7363
  intensity           0           0
  return_number       1           1
  number_of_returns   1           1
  edge_of_flight_line 0           0
  scan_direction_flag 0           0
  classification      1           6
  scan_angle_rank     0           0
  user_data           0         255
  point_source_ID     0           0
number of first returns:        1460134
number of intermediate returns: 0
number of last returns:         1460134
number of single returns:       1460134
overview over number of returns of given pulse: 1460134 0 0 0 0 0 0
histogram of classification of points:
          514129  unclassified (1)
          713525  ground (2)
           95468  high vegetation (5)
          137012  building (6)
```

Figure 58: LASinfo of the lidar data after classification

Next we will create a DTM from the classified lidar using LAS2DEM. We will just use the classified ground points. So, we will keep classification 2. We are only looking for ground points with a DTM. We will also thin some of the data to every half meter; 0.5 by 0.5. This will keep the memory storage lower for easier control in the future. We will also have it make two passes over the data. The first pass it only counts the number of points that pass through the filter and the second pass can optimize the memory used to triangulate them. For the output, we used the BIL format. We could use the ASC because it stores the values as ASCII text which is terribly inefficient and much slower to read than BIL format.

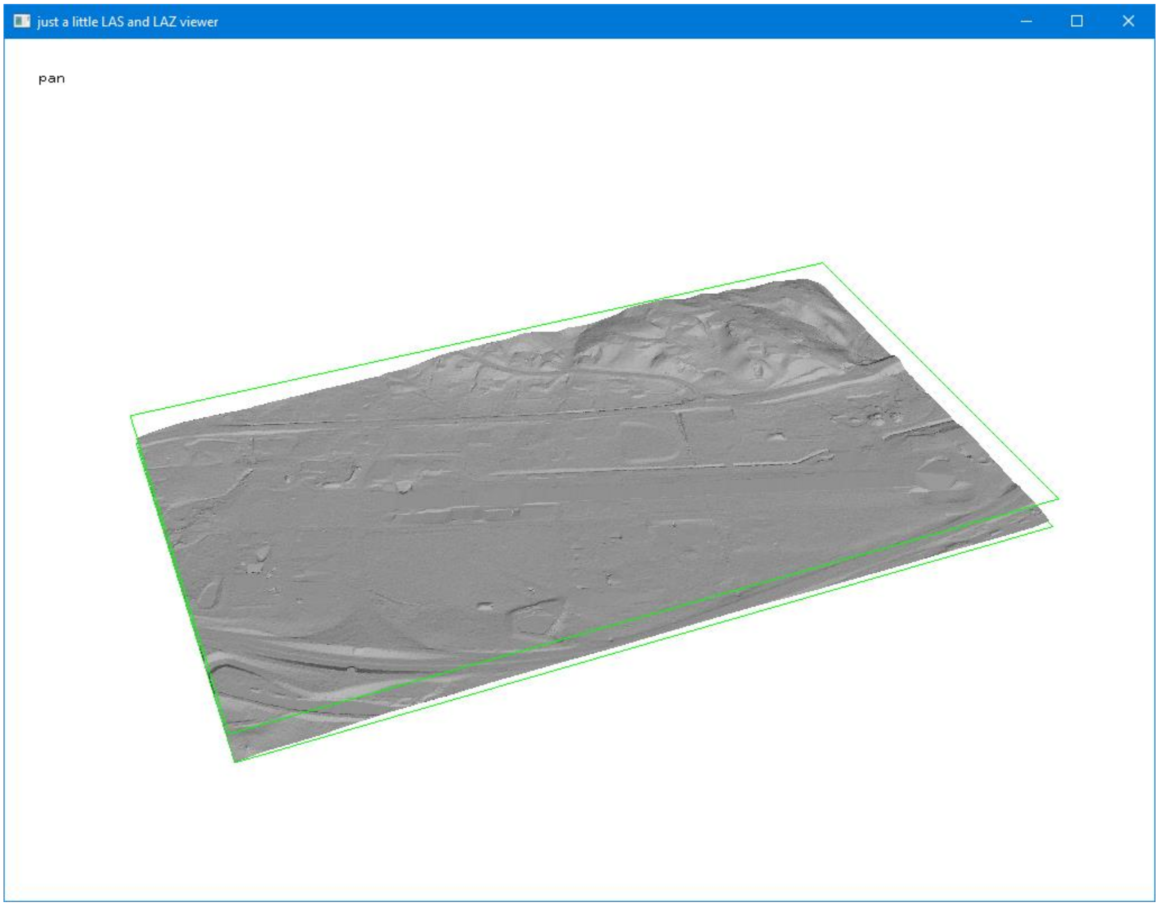


Figure 59: View of DTM for warfare center

For creating a DSM, we will use a similar approach as we did with creating a DTM but instead of using the ground points as a reference, we will use the first return only instead of the ground points.

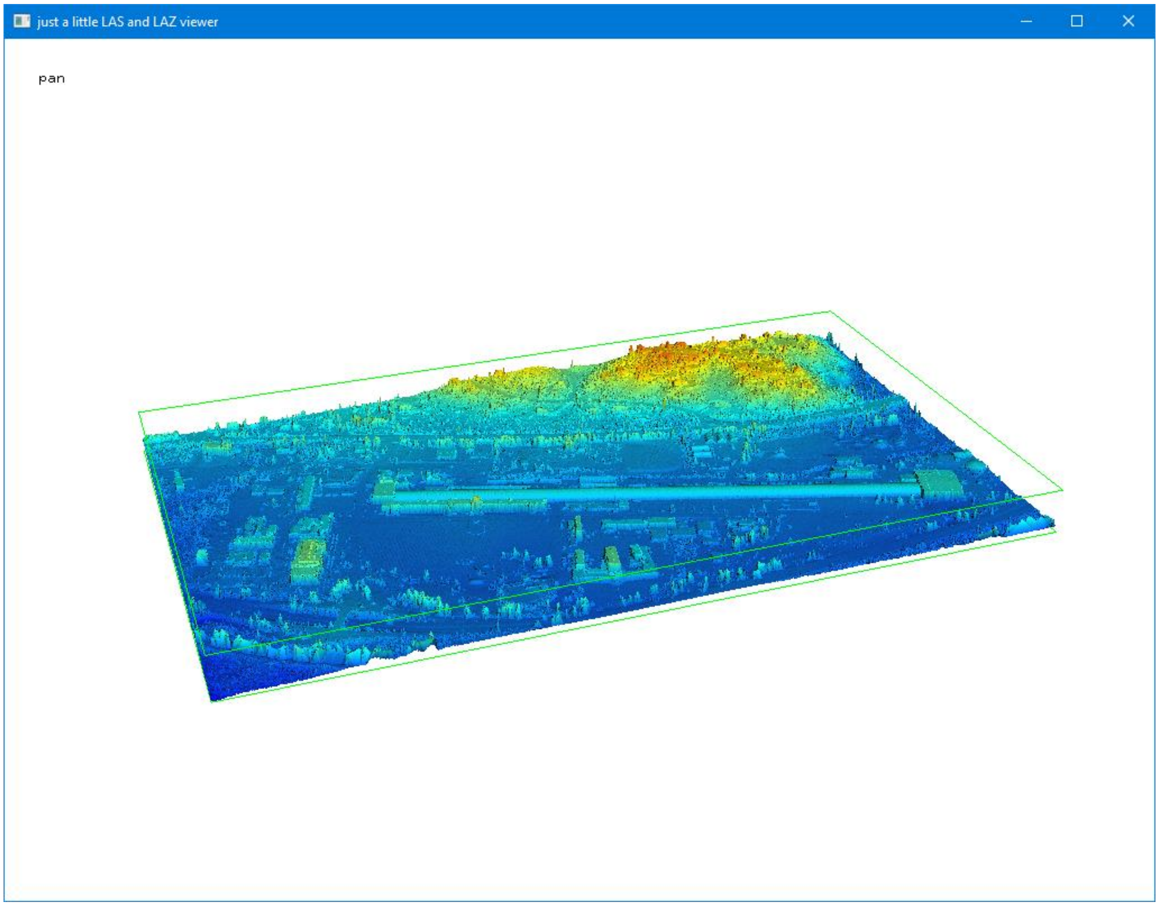


Figure 60: View of DSM for the warfare center

Generation of contours will be our next step. We will create contours with a one meter interval from the DTM data and store them as a Shapefile. We will use the tool BLASt2iso for this task. We will also choose to simplify short segments, simplify small bumps, and clean short lines. This option will eliminate contours crossing one another and short segments will be removed from the final product.

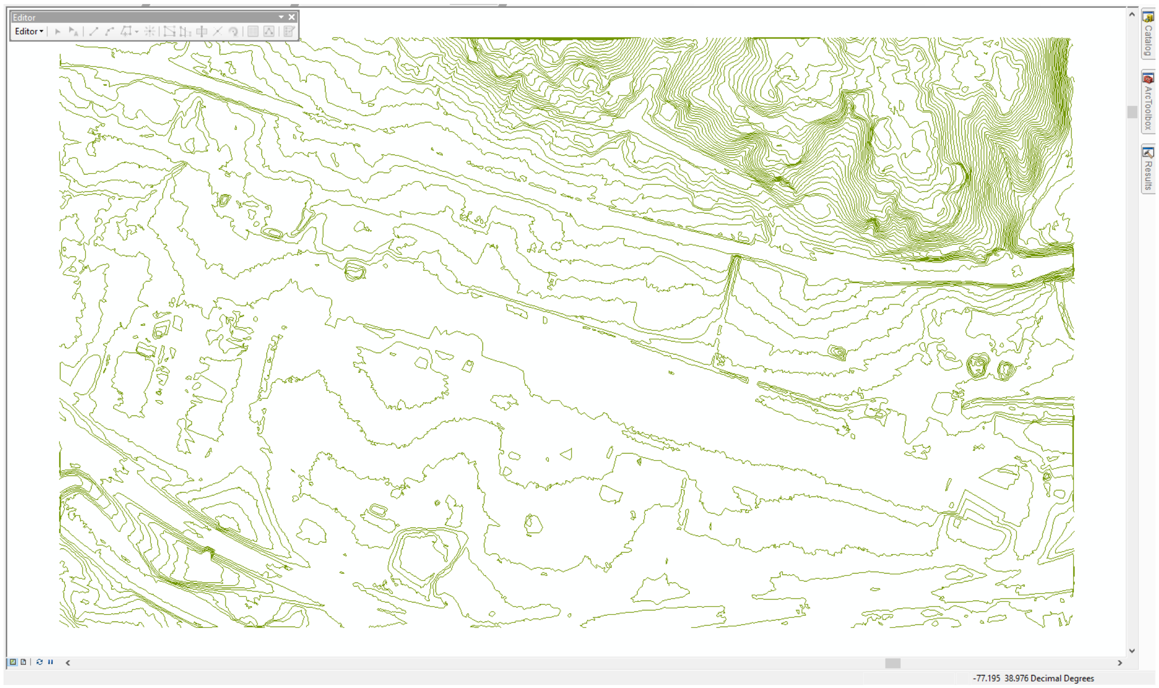


Figure 61: Contour of 1 meter interval with DTM displayed in ArcGIS

Now likes look at a DSM contour with a three-meter interval instead of one meter.

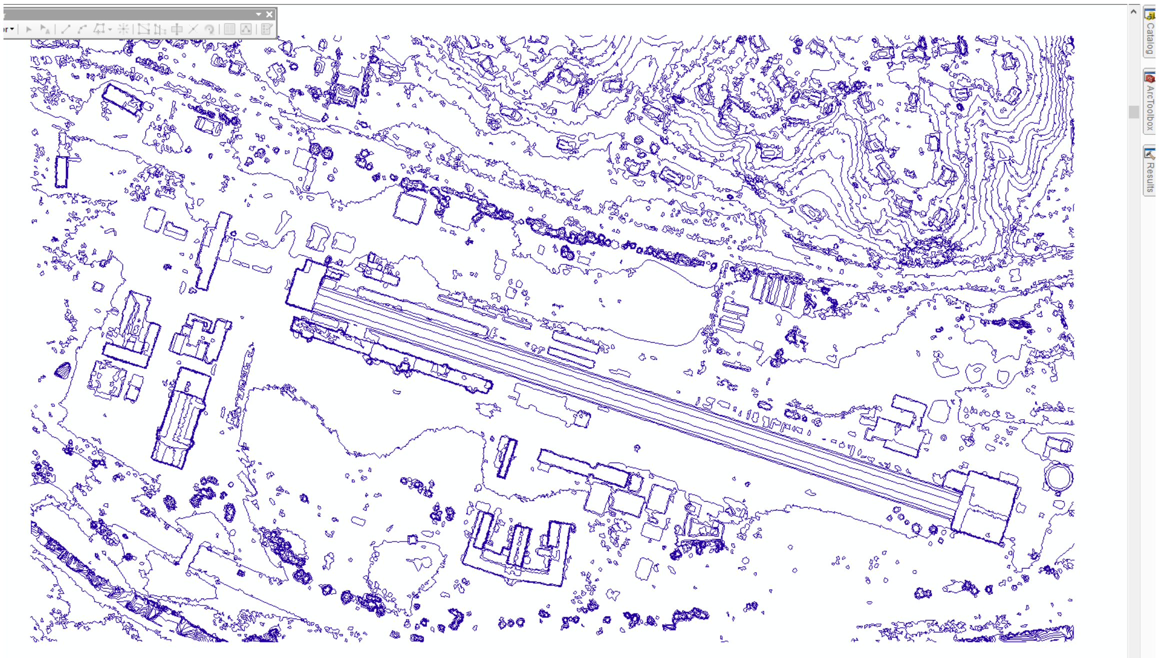


Figure 62: Contour of 3 meter interval with DSM displayed in ArcGIS

Instead of digitizing all the buildings, we will use LASBoundary to extract all the buildings. We will use the classified LAZ files and filter out everything except for the classify 6; buildings. There are options for different settings to get the desired results we want. Here is an example of using 3 meter search area size with a 2 meter concavity on all points classified as a building.

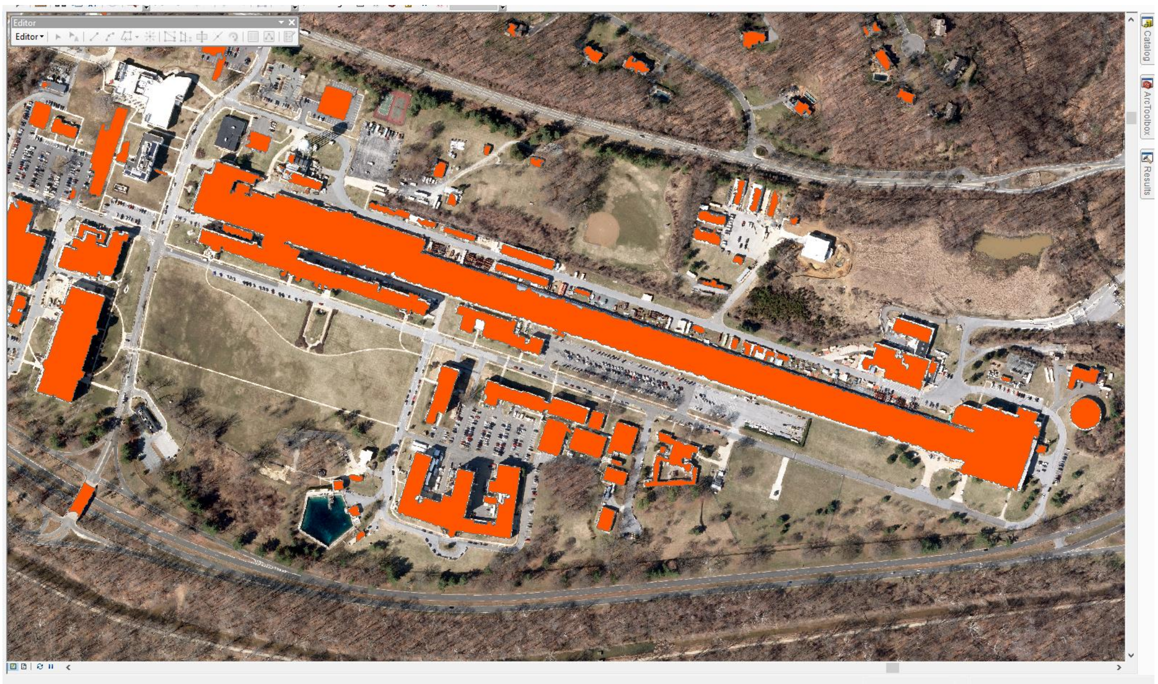


Figure 63: LASBoundary for warfare center using 3 meter search area and 2 meter concavity displayed in ArcGIS

Let us see if we can tweak our results more. We will go back to LAS classify and use a search are of 2 meters compared to three meters and see what our results are. The 2-meter search area size with a 2-meter concavity on all points classified as a building is in yellow with a 50% transparency. The 3-meter search area size with a 2-meter concavity on all points classified as a building is in red. The orange tint is where they both agree. Red is where only the 3-meter search area size and yellow is only the 2-meter search area size. For this area, 2-meter search size area works best.

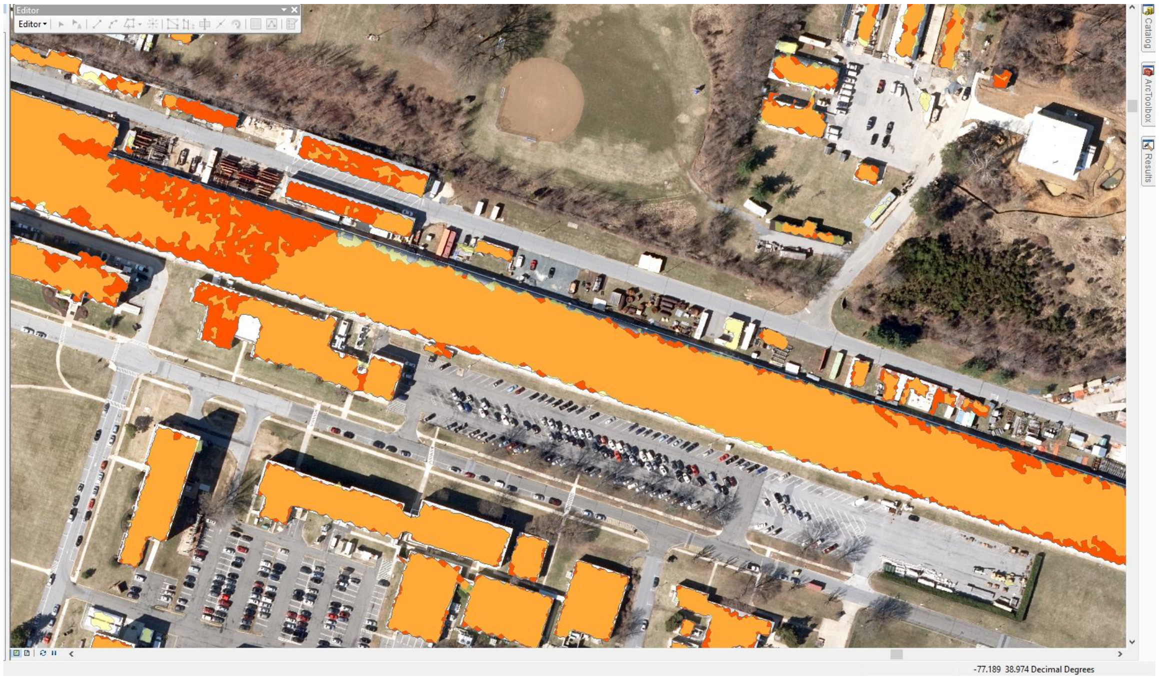


Figure 64: LASBoundary comparison for warfare center using 3 meter search area and 2 meter search area

Now that we extracted our building shapefiles and compared them to the imagery, time for us to do some final edits to the lidar. I pulled up the area in Bing maps to get a better view of a smaller and more detailed area.

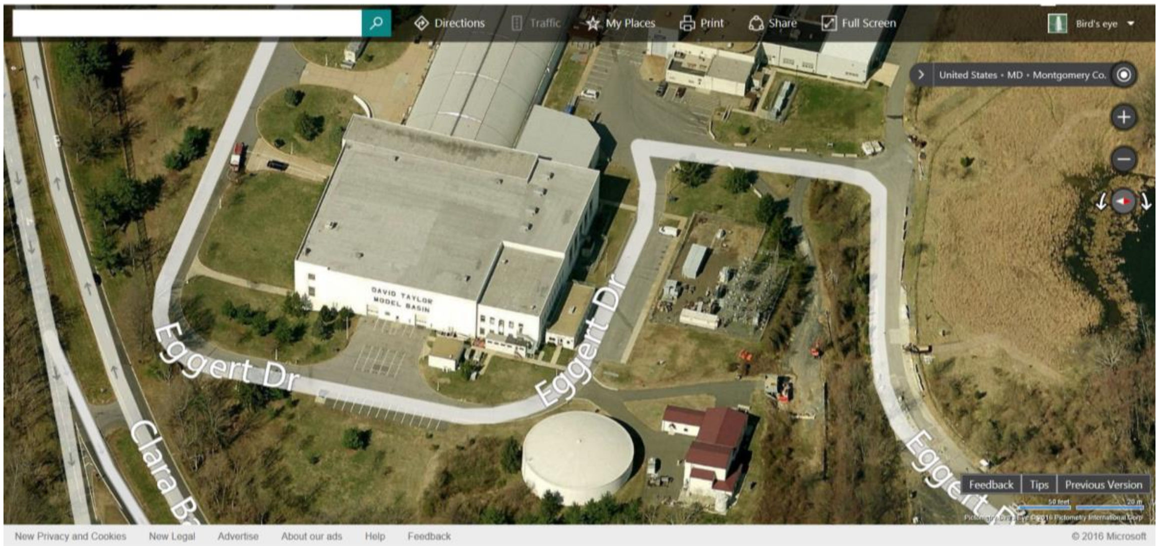


Figure 65: Bing image of warfare center

In the lidar points, you can a similar elevation difference. One of the easiest things is the top of the water tower since it has a domed look. The orange pixels are the buildings, green is vegetation, Black is unknown points and red-brown is the ground points.

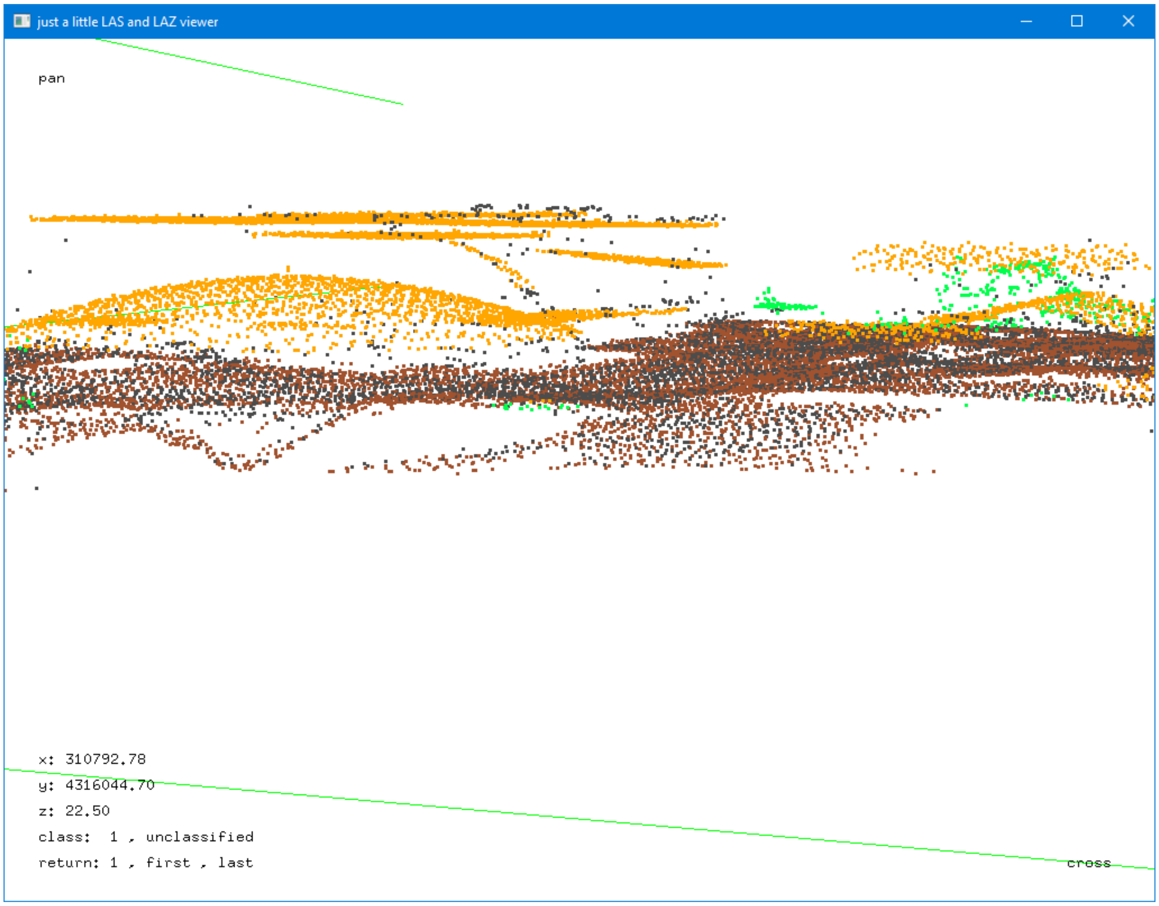


Figure 66: LASView edit of the smaller area of warfare center

You can triangulate the points to get a better picture of the lidar points. With a LAS tool license or smaller area, you can easily make edits to all the features. You can change what the tool originally classified the points. You can change point classification because buildings, vegetation, ground points, and unclassified points. Some points are just noise from the lidar points and they can be deleted to clean up the data.

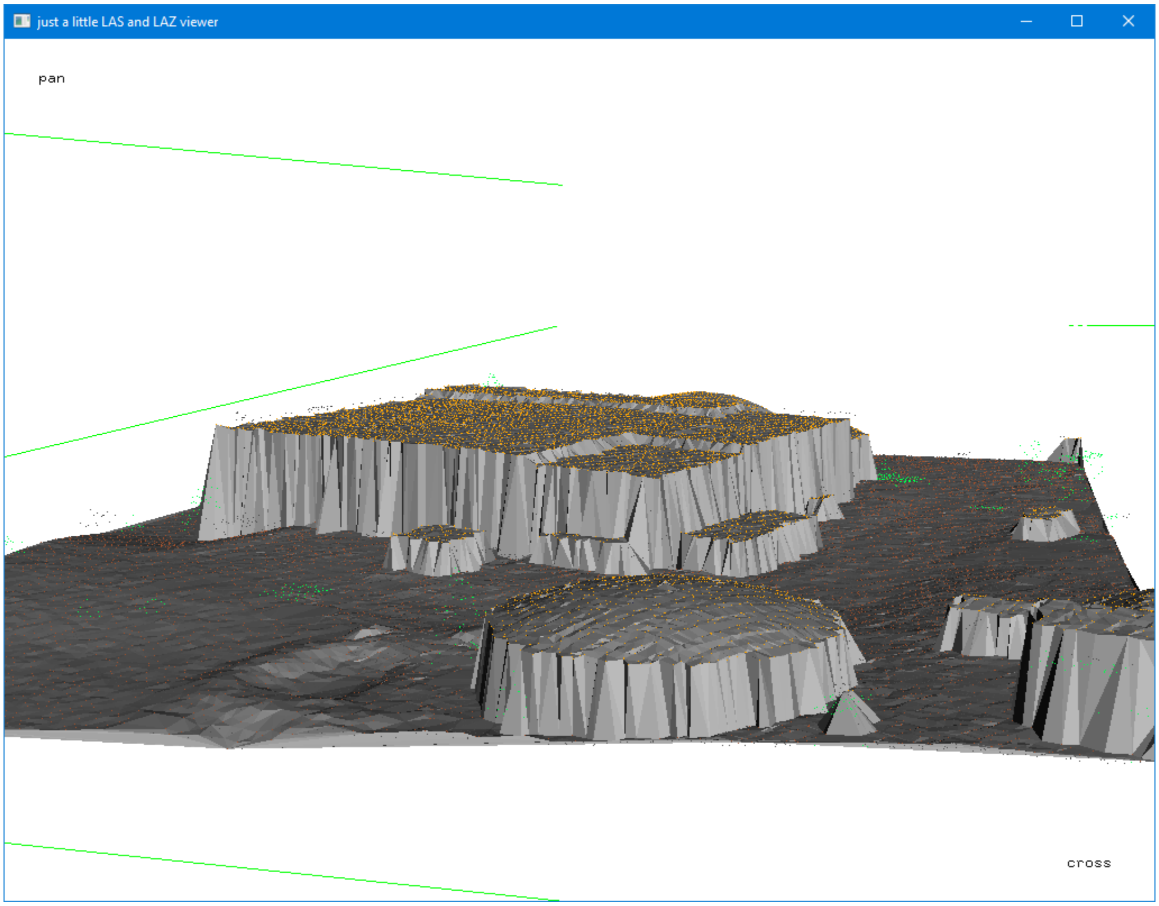


Figure 67: Triangulated data after data cleanup of the smaller area of the warfare center

Here is a somewhat similar view in ArcGIS of the lidar data and a 3D look from the side.

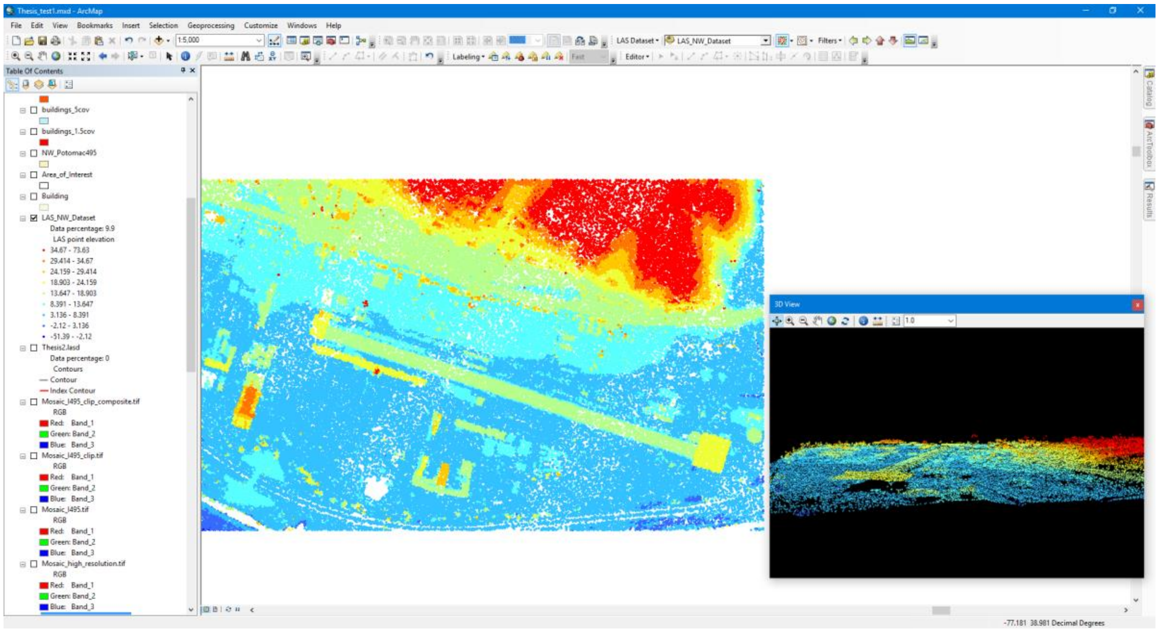


Figure 68: ArcGIS view of the lidar data from above and 3D side view

Next we will compare SRTM data to Lidar data in the area of interest. Below is a screenshot of SRTM data in the area compared to the lidar data. Obviously, the Lidar data has a much higher density compared to the SRTM. The SRTM is very blocky compared to the smoother Lidar data. SRTM data covers most the earth's surface while Lidar is only a small portion. As you can see the difference you should think about the data storage capacity. With so much data in lidar, it would be difficult to survey the world and then later store that data for practical use.

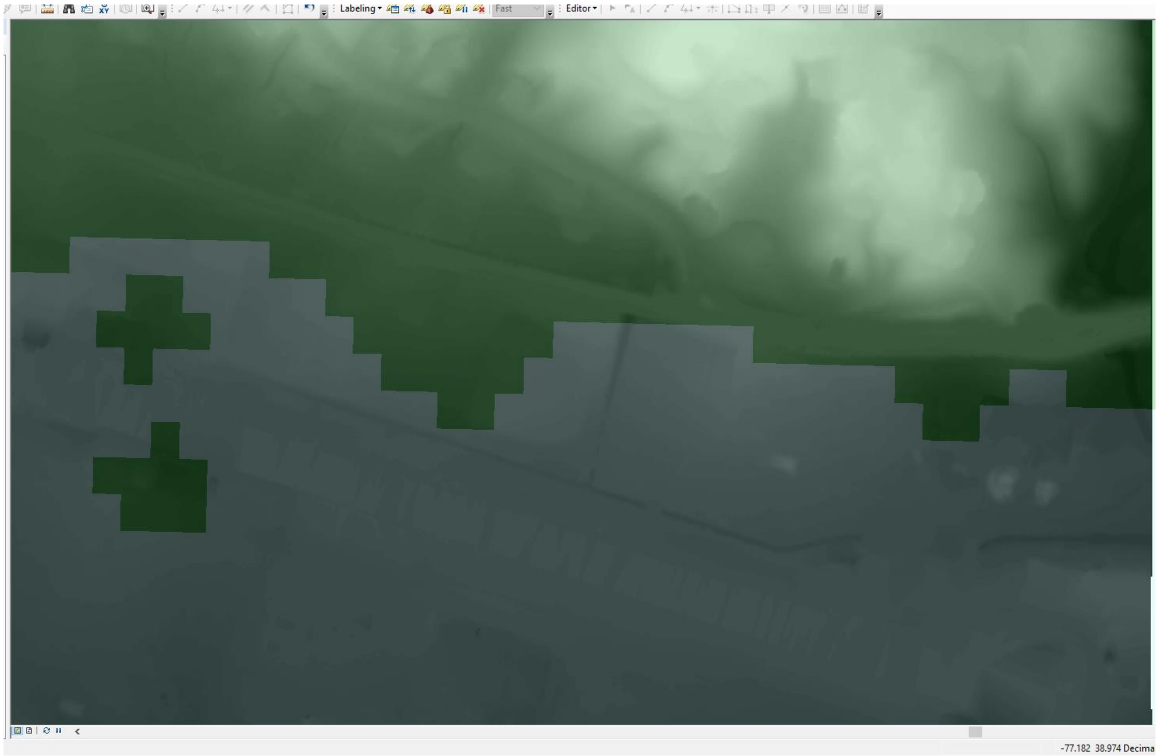


Figure 69: SRTM data compared to Lidar data

It is obvious to see the difference between SRTM and Lidar datasets, but what about projection differences. Earlier in the paper we mentioned the importance of projections. Projections in mapping are a crucial factor that is normally ignored our not thought off. There are hundreds of projections in the world and if you work with international partners and in different locations in the world then projections became a crucial part of the process. Even in the United States there are many projections tied to different datums. In the United States many people still work in feet while others work in meters like most of the people throughout the world.

I took the Buildings_2cov.shp that I displayed earlier and did a define projection to NAD1927 UTM 18N then I projected it to NAD83 UTM 18N. Since the initial define projection was an error, it projected the whole shapefile approximately 221 meters off what it should be. A simple task as not knowing the correct projection of the data can have devastating consequences.

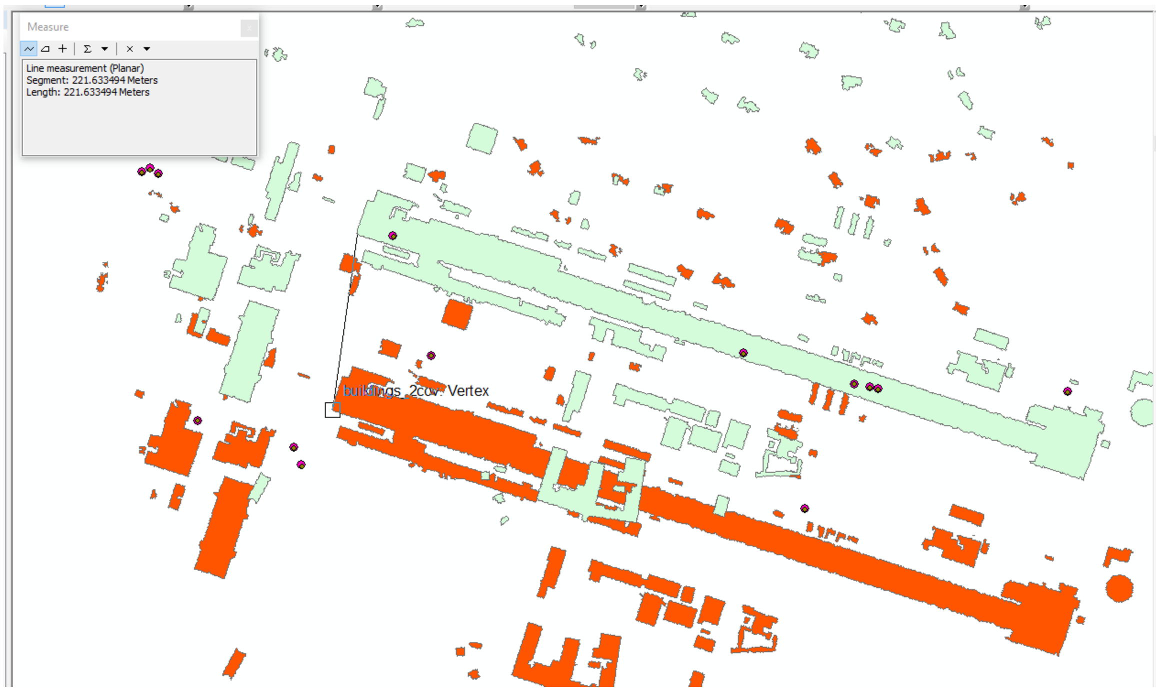


Figure 70: Projection error of warfare center

For a precision example of the lidar data, I ran another program called LASprecision to show the accuracy of the lidar data to itself.

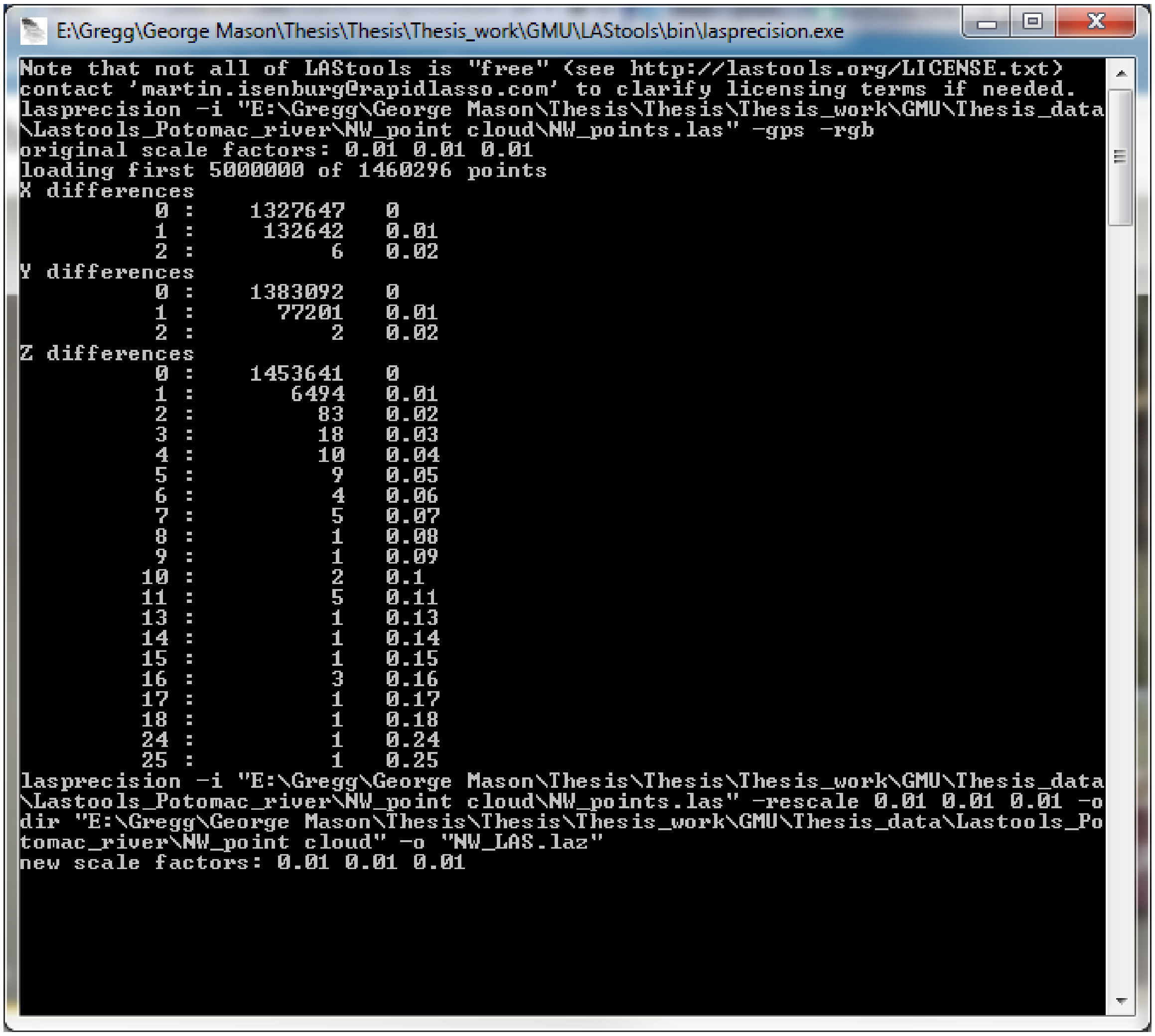


Figure 71: LASPrecision of warfare center lidar

CHAPTER 8: TERRESTRIAL LIDAR

Aside from airborne Lidar datatypes, land based lidar scanners are used as well. The terrestrial lidar survey was carried out in an area covering ~60 m by ~100 m in the Granite Dells precarious rock zone near Prescott, Arizona. It spanned a small mixed alluvial-bedrock channel that is flanked by precariously balanced rock covered hillslopes. The survey was scanned with a tripod mounted Riegl LPM 321 terrestrial Laser scanner.

Section One: Open Topography and USGS Earth Explorer

The Lidar was downloaded from Open Topography. To finish out the rest of the data needed we downloaded SRTM and high resolution ortho-imaged Imagery from USGS Earth Explorer site.

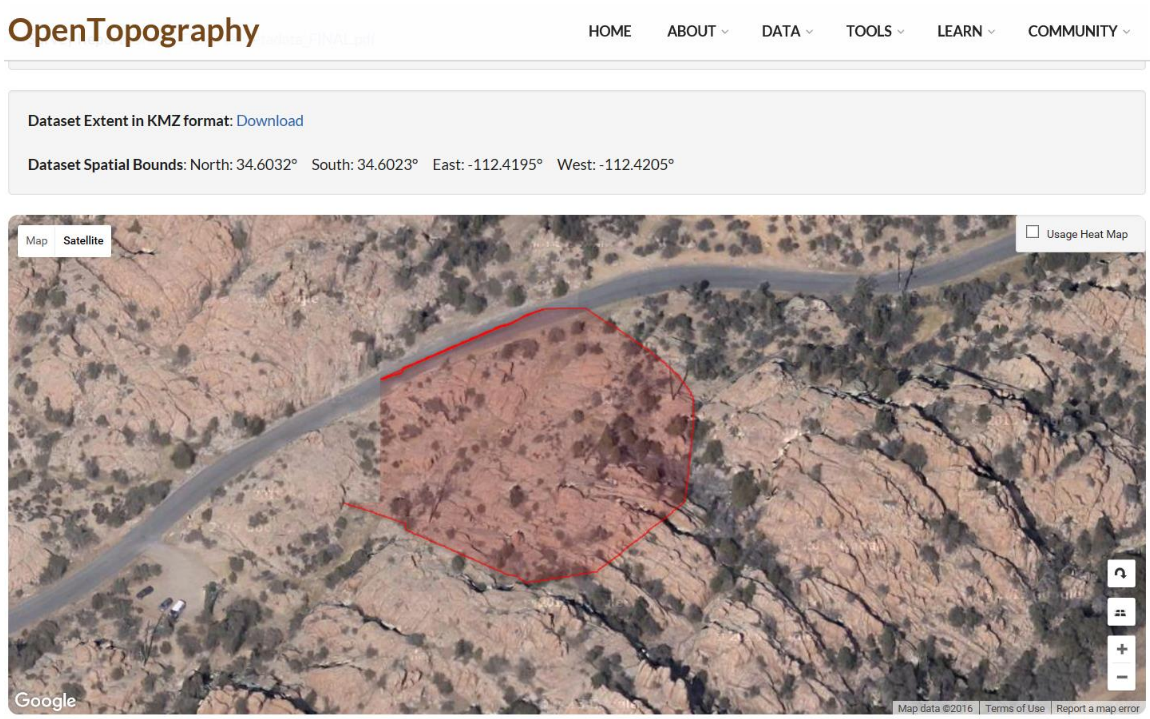


Figure 72: Open Topography screenshot of the area of interest

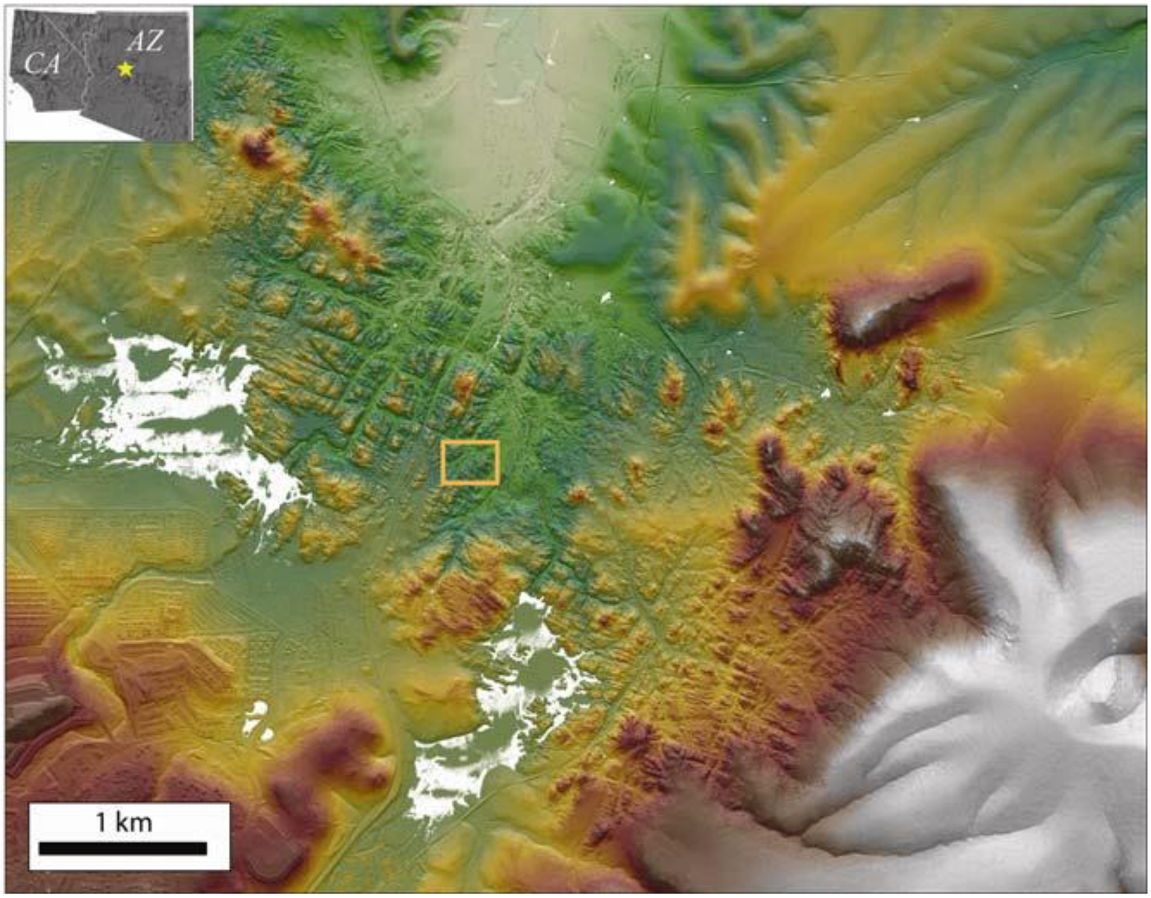


Figure 73: Survey area overview for terrestrial survey, Prescott, Arizona

Section Two: Processing Lidar with LAStools

To comply with LAStools unlicensed limits, a smaller section of the lidar was downloaded. The initial download was around five million points and the newer section was 1,873,344 points instead. I first processed the smaller subset and then later the full version. We will first look at the lidar data in LASInfo before any data manipulation occurs.

```
NorthRoad.txt - Notepad
File  Edit  Format  View  Help
  record ID              34735
  length after header    96
  description            'GeoTIFF GeoKeyDirectoryTag'
    GeoKeyDirectoryTag version 1.1.0 number of keys 11
      key 1024 tiff_tag_location 0 count 1 value_offset 1 - GTModelTypeGeoKey: ModelTypeProjected
      key 1025 tiff_tag_location 0 count 1 value_offset 1 - GTRasterTypeGeoKey: RasterPixelIsArea
      key 1026 tiff_tag_location 34737 count 31 value_offset 0 - GTCitationGeoKey: NAD83 / UTM zone 12N + VERT_CS
      key 2049 tiff_tag_location 34737 count 6 value_offset 31 - GeogCitationGeoKey: NAD83
      key 2054 tiff_tag_location 0 count 1 value_offset 9102 - GeogAngularUnitsGeoKey: Angular_Degree
      key 3072 tiff_tag_location 0 count 1 value_offset 26912 - ProjectedCSTypeGeoKey: NAD83 / UTM 12N
      key 3076 tiff_tag_location 0 count 1 value_offset 9001 - ProjLinearUnitsGeoKey: Linear_Meter
      key 4096 tiff_tag_location 0 count 1 value_offset 5703 - VerticalCSTypeGeoKey: NAVD88 height (Reserved EPSG)
      key 4097 tiff_tag_location 34737 count 14 value_offset 37 - VerticalCitationGeoKey: NAVD88 height
      key 4098 tiff_tag_location 0 count 1 value_offset 5103 - VerticalDatumGeoKey: Vertical Datum Codes 5103
      key 4099 tiff_tag_location 0 count 1 value_offset 9001 - VerticalUnitsGeoKey: Linear_Meter
variable length header record 2 of 3:
  reserved               43707
  user ID                'LASF_Projection'
  record ID              34737
  length after header    51
  description            'GeoTIFF GeoAsciiParamsTag'
    GeoAsciiParamsTag (number of characters 51)
      NAD83 / UTM zone 12N + VERT_CS|NAD83|NAVD88 height|
variable length header record 3 of 3:
  reserved               43707
  user ID                'liblas'
  record ID              2112
  length after header    951
  description            'OGR variant of OpenGIS WKT SRS'
reporting minimum and maximum for all LAS point record entries ...
  X             36976057   36983698
  Y            382992907  382995708
  Z               154556     155314
  intensity            0          0
  return_number        0          0
  number_of_returns    0          0
  edge_of_flight_line  0          0
  scan_direction_flag  0          0
  classification       0          0
  scan_angle_rank      0          0
  user_data            0          0
  point_source_ID      0          0
number of first returns:        1873344
number of intermediate returns: 0
number of last returns:         1873344
number of single returns:       1873344
WARNING: there are 1873344 points with return number 0
WARNING: there are 1873344 points with a number of returns of given pulse of 0
histogram of classification of points:
         1873344  never classified (0)
```

Figure 74: LASInfo of the smaller section of terrestrial survey

Now we will start the lidar processing and we will run LAS ground. This is a bare earth extraction tool that will classify the data as ground points, class = 2, or non-ground points, class = 1. This tool only looks at the last return for consideration. For this area, we will use the nature method for classification. The area of interest is a bare hilly area with no buildings. Because of the steepness of the area we will set the settings to search for initial ground points with hyper and then that later I tried ultra with very little difference. The first screen shot is using hyper and the second one is using ultra. I had the elevation colored in for the second one.

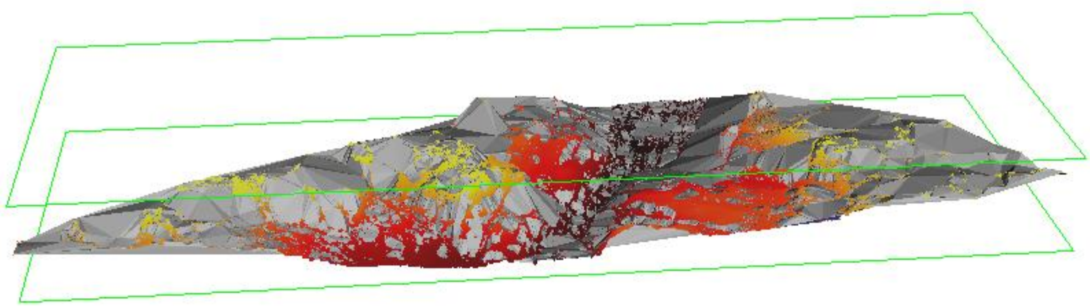


Figure 75: LASground using hyper search setting

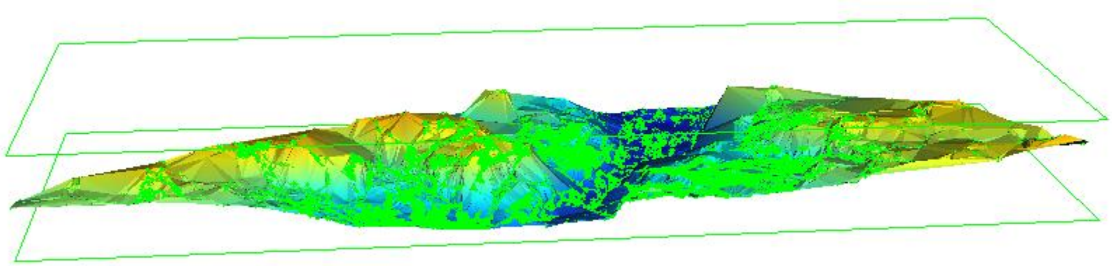


Figure 76: LASground using ultra search setting

Next we will use LAS height to drop all the ground points that are below 2 meter and above 30 meters. Now we will take those heights and classify them using LASClassify.

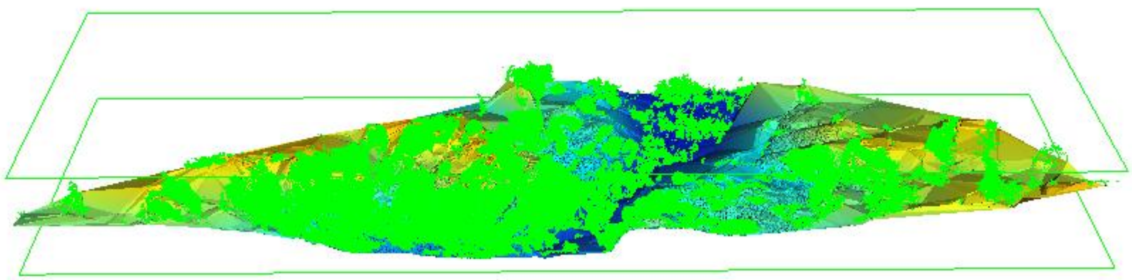
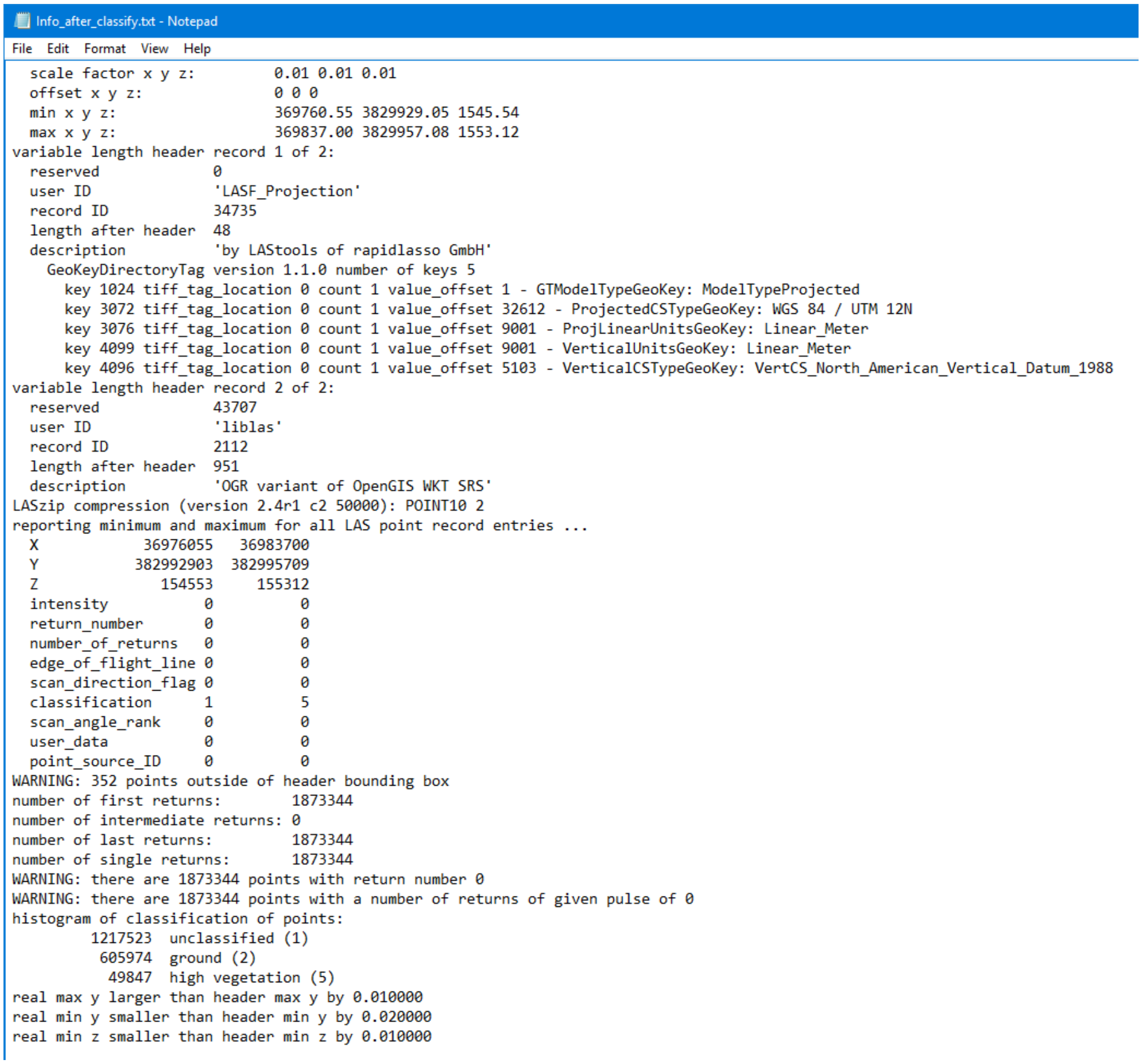


Figure 77: LASclassify of terrestrial survey area

I ran LASinfo after the classify process to look at the metadata of the lidar and a closer screenshot of the area.



Info_after_classify.txt - Notepad

File Edit Format View Help

```
  scale factor x y z:         0.01 0.01 0.01
  offset x y z:               0 0 0
  min x y z:                  369760.55 3829929.05 1545.54
  max x y z:                  369837.00 3829957.08 1553.12
variable length header record 1 of 2:
  reserved             0
  user ID              'LASF_Projection'
  record ID            34735
  length after header  48
  description          'by LAStools of rapidlasso GmbH'
    GeoKeyDirectoryTag version 1.1.0 number of keys 5
      key 1024 tiff_tag_location 0 count 1 value_offset 1 - GTModelTypeGeoKey: ModelTypeProjected
      key 3072 tiff_tag_location 0 count 1 value_offset 32612 - ProjectedCSTypeGeoKey: WGS 84 / UTM 12N
      key 3076 tiff_tag_location 0 count 1 value_offset 9001 - ProjLinearUnitsGeoKey: Linear_Meter
      key 4099 tiff_tag_location 0 count 1 value_offset 9001 - VerticalUnitsGeoKey: Linear_Meter
      key 4096 tiff_tag_location 0 count 1 value_offset 5103 - VerticalCSTypeGeoKey: VertCS_North_American_Vertical_Datum_1988
variable length header record 2 of 2:
  reserved             43707
  user ID              'liblas'
  record ID            2112
  length after header  951
  description          'OGR variant of OpenGIS WKT SRS'
LASzip compression (version 2.4r1 c2 50000): POINT10 2
reporting minimum and maximum for all LAS point record entries ...
  X            36976055   36983700
  Y           382992903  382995709
  Z              154553     155312
  intensity           0          0
  return_number       0          0
  number_of_returns   0          0
  edge_of_flight_line 0          0
  scan_direction_flag 0          0
  classification      1          5
  scan_angle_rank     0          0
  user_data           0          0
  point_source_ID     0          0
WARNING: 352 points outside of header bounding box
number of first returns:        1873344
number of intermediate returns: 0
number of last returns:         1873344
number of single returns:       1873344
WARNING: there are 1873344 points with return number 0
WARNING: there are 1873344 points with a number of returns of given pulse of 0
histogram of classification of points:
         1217523  unclassified (1)
          605974  ground (2)
           49847  high vegetation (5)
real max y larger than header max y by 0.010000
real min y smaller than header min y by 0.020000
real min z smaller than header min z by 0.010000
```

Figure 78: LASinfo after classification of smaller terrestrial area

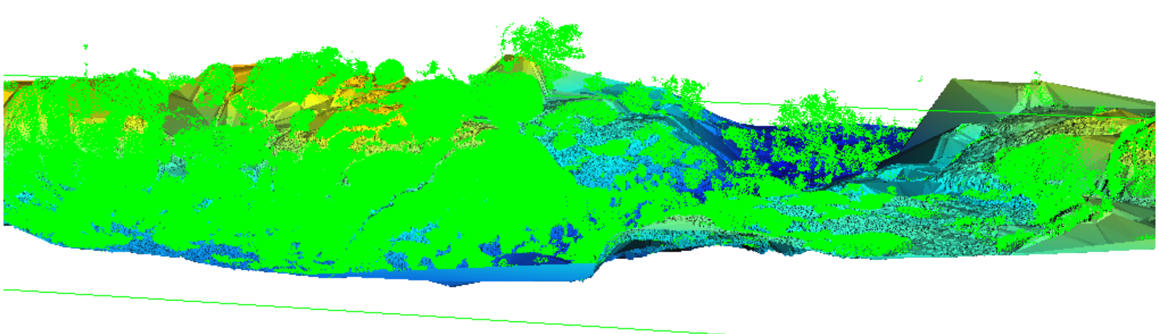


Figure 79: Closer view of classified area of smaller section

With this smaller area and having white noise introduced you can see some contours after the DTM, DSM and Contouring processing. The area is approximately 77 meters at the widest point.

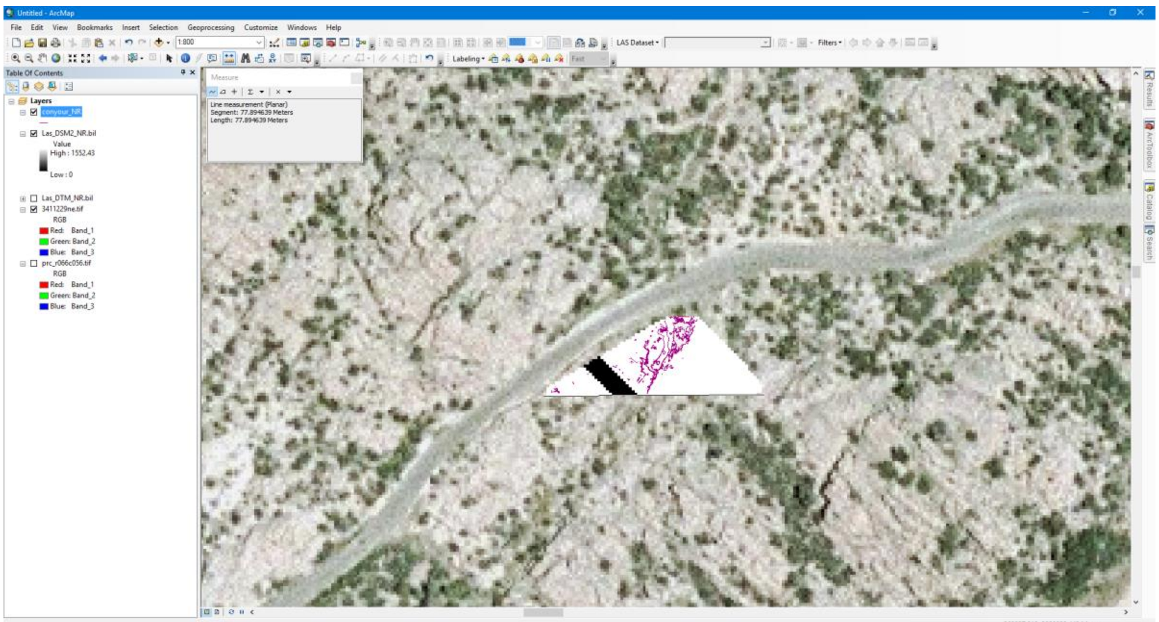


Figure 80: Contour area of smaller section shown in ArcGIS

With this small of an area that already has white noise added because of the unlicensed LAStools we will look at the whole section. We will run through the same process as above.

```
full_info.txt - Notepad
File  Edit  Format  View  Help
  record ID             34735
  length after header   96
  description           'GeoTIFF GeoKeyDirectoryTag'
    GeoKeyDirectoryTag version 1.1.0 number of keys 11
      key 1024 tiff_tag_location 0 count 1 value_offset 1 - GTModelTypeGeoKey: ModelTypeProjected
      key 1025 tiff_tag_location 0 count 1 value_offset 1 - GTRasterTypeGeoKey: RasterPixelIsArea
      key 1026 tiff_tag_location 34737 count 31 value_offset 0 - GTCitationGeoKey: NAD83 / UTM zone 12N + VERT_CS
      key 2049 tiff_tag_location 34737 count 6 value_offset 31 - GeogCitationGeoKey: NAD83
      key 2054 tiff_tag_location 0 count 1 value_offset 9102 - GeogAngularUnitsGeoKey: Angular_Degree
      key 3072 tiff_tag_location 0 count 1 value_offset 26912 - ProjectedCSTypeGeoKey: NAD83 / UTM 12N
      key 3076 tiff_tag_location 0 count 1 value_offset 9001 - ProjLinearUnitsGeoKey: Linear_Meter
      key 4096 tiff_tag_location 0 count 1 value_offset 5703 - VerticalCSTypeGeoKey: NAVD88 height (Reserved EPSG)
      key 4097 tiff_tag_location 34737 count 14 value_offset 37 - VerticalCitationGeoKey: NAVD88 height
      key 4098 tiff_tag_location 0 count 1 value_offset 5103 - VerticalDatumGeoKey: Vertical Datum Codes 5103
      key 4099 tiff_tag_location 0 count 1 value_offset 9001 - VerticalUnitsGeoKey: Linear_Meter
variable length header record 2 of 3:
  reserved              43707
  user ID               'LASF_Projection'
  record ID             34737
  length after header   51
  description           'GeoTIFF GeoAsciiParamsTag'
    GeoAsciiParamsTag (number of characters 51)
      NAD83 / UTM zone 12N + VERT_CS|NAD83|NAVD88 height|
variable length header record 3 of 3:
  reserved              43707
  user ID               'liblas'
  record ID             2112
  length after header   951
  description           'OGR variant of OpenGIS WKT SRS'
reporting minimum and maximum for all LAS point record entries ...
  X             36974534   36984060
  Y            382986143  382995708
  Z               154556     156623
  intensity            0          0
  return_number        0          0
  number_of_returns    0          0
  edge_of_flight_line  0          0
  scan_direction_flag  0          0
  classification       0          0
  scan_angle_rank      0          0
  user_data            0          0
  point_source_ID      0          0
number of first returns:        4977693
number of intermediate returns: 0
number of last returns:         4977693
number of single returns:       4977693
WARNING: there are 4977693 points with return number 0
WARNING: there are 4977693 points with a number of returns of given pulse of 0
histogram of classification of points:
         4977693  never classified (0)
```

Figure 81: LASinfo of full view of terrestrial survey

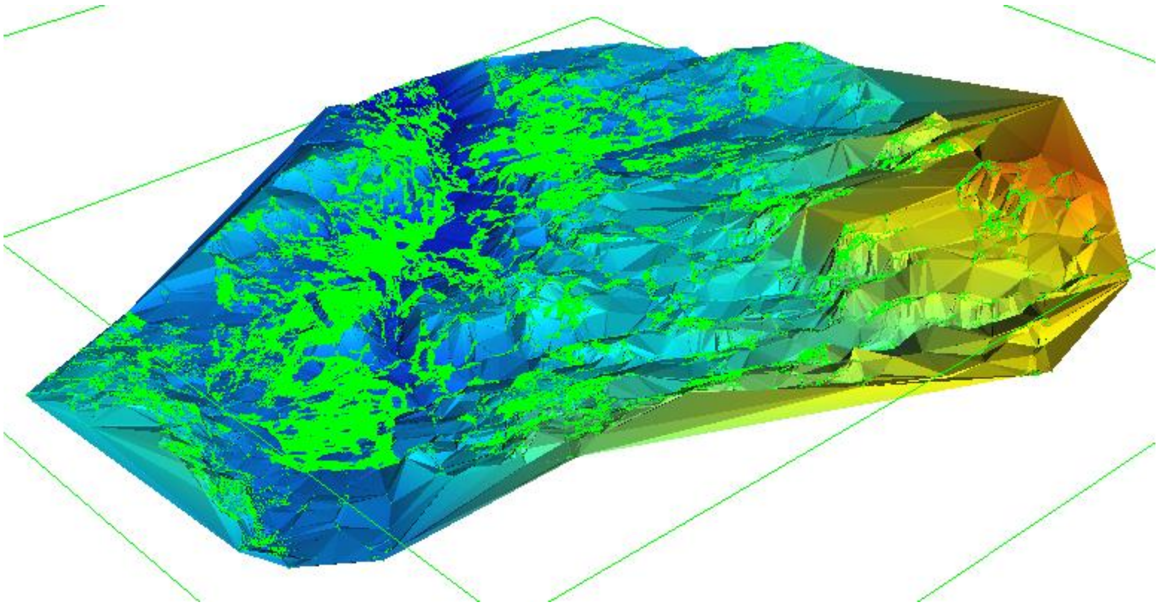


Figure 82: LASGround full view of terrestrial survey

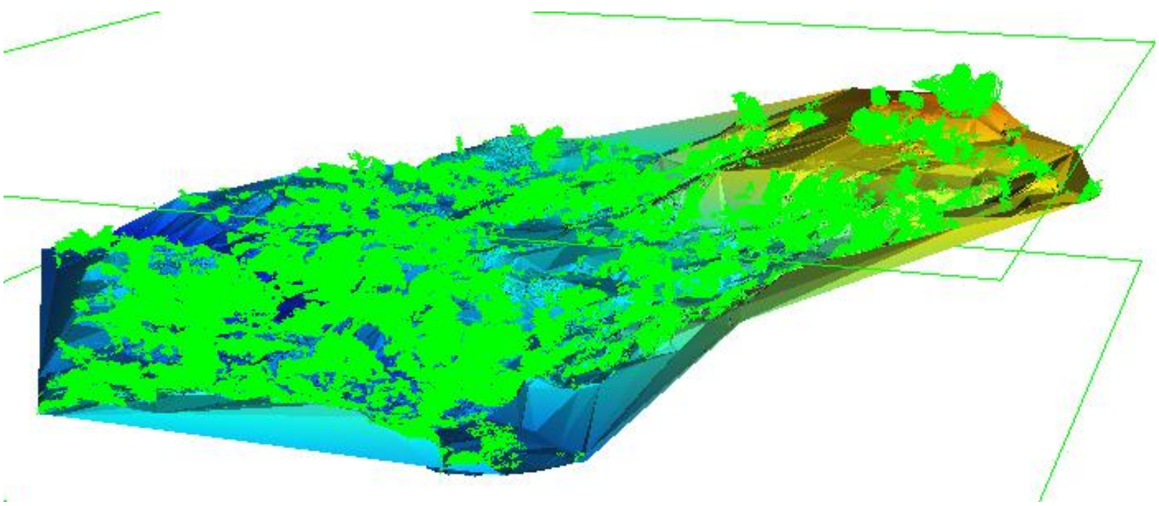


Figure 83: LASClassify full view of terrestrial survey

This first area was done on a small area: approximately 95 meters at the widest point. The stripe is caused by having an unlicensed version of LAS Tools. Both areas are over one million points. The screen shot shows the DSM for both the smaller and full view of the terrestrial survey.

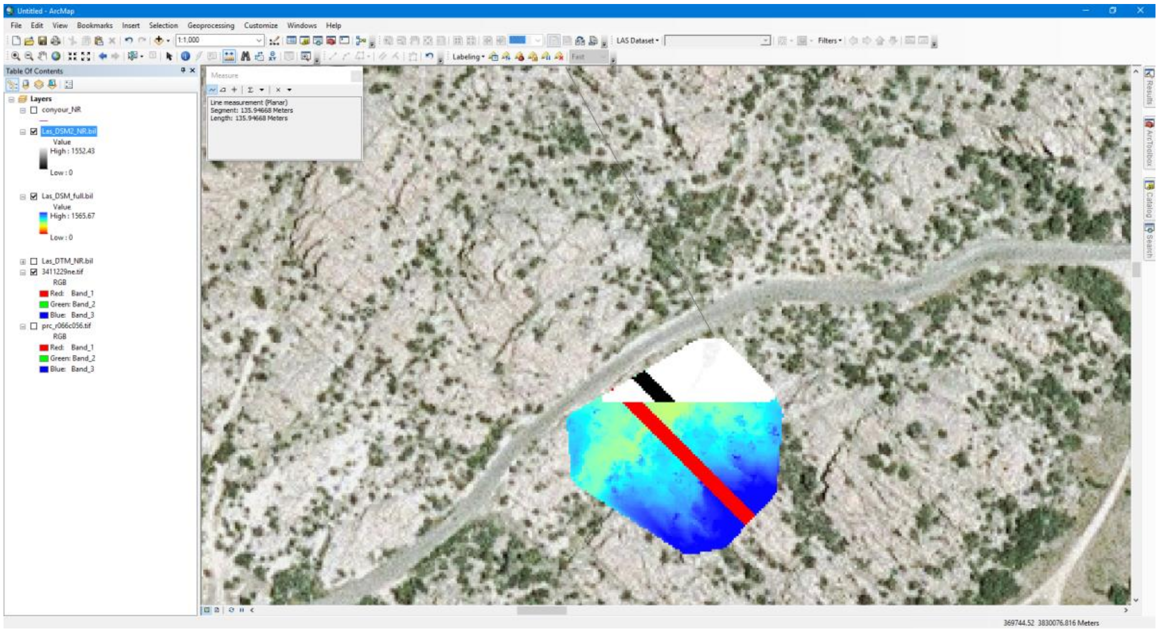


Figure 84: DSM of both sections shown in ArcGIS

CHAPTER 9: SUMMARY

This paper clearly states the accuracy and importance of lidar in our modern day life. Throughout this paper we have discussed where lidar came from and how it has matured. We also discussed how it is used it has been used in everyday life. There are three major types of lidar; Airborne, Mobile, and Terrestrial. Airborne is the most common type for mapping. Mobile is commonly used in our vehicle systems. Terrestrial lidar is used for smaller areas that can have higher point cloud density. An important element of lidar is the survey control points and what datum and projection it has. Lidar with common datum between the data and control points is crucial step. Having different datums would jeopardize any accuracy.

In the thesis, we actually used real data and LAStools to process it. We went through many of the tools that are needed in the process of lidar data; Quality checking, Data Preparation, Derivative production, and editing LAS files. Initially you must check the quality of the data before processing. If the data is irrelevant then it would be useless to process the data. The next step is data preparation. It is the process of taking the data and manipulating the data to pull out the heights and identifying features with it. The third step is to derive products. Depending on your customer, you will want to create certain products for customer use; contours, building boundaries, DTM, DSM, etc. Another step that may need to be applied is editing the LAS files. The Lidar process is not 100%; nothing is perfect. The system may classify lidar point cloud points as noise points when they are actually a building or vegetation. This can be a time consuming job depending on where the area of interest is; urban, mountains, forest, etc. You can also try different modifications to the tools in LAStools to get a crisper product.

After going through many of the procedures to manipulate lidar data, there were three different experiments performed; two small and one major experiment. In Chapter 6, Kameni Islands, we processed lidar data and then covered it with imagery. In Chapter 7, Potomac River experiment, we processed lidar data and compared it with control points, imagery, and SRTM data. SRTM data is gridded into 30 meter square tiles areas compared to centimeters for lidar. Accuracy for SRTM data is approximately 20 meters for horizontal and 10 meters for vertical. Lidar accuracy was approximately three meters from some control points but can be adjusted and the vertical precision was between centimeter and decimeter accuracy. The last experiment, Chapter 8, was to show the difference in terrestrial lidar compared to airborne lidar. It was a smaller area with higher point density.

Lidar is the future of elevation data. It is a more detailed data set than the traditional SRTM, DTED or other DEMs used in the Geospatial community. Besides the data storage, lidar data is far more superior in accuracy and point spacing. Lidar can also be used with other sources to improve their efficiency.

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