This module will provide an introduction to light detection and ranging, or LiDAR. This technology offers a means to generate detailed, high spatial resolution 3D models and terrain surfaces. It has revolutionized elevation mapping and modeling.

Module Topics

1. Lidar core concepts
2. Data collection methods
3. Point cloud visualization
4. Point cloud filtering
5. Point cloud rasterization
6. Lidar applications
7. Lidar processing tools and software

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These are the topics covered in this module.

Video: Intro to LiDAR

Video from TED

https://www.youtube.com/watch?v=B6rIUxHZ9f4&t=41s

Digital Elevation Data

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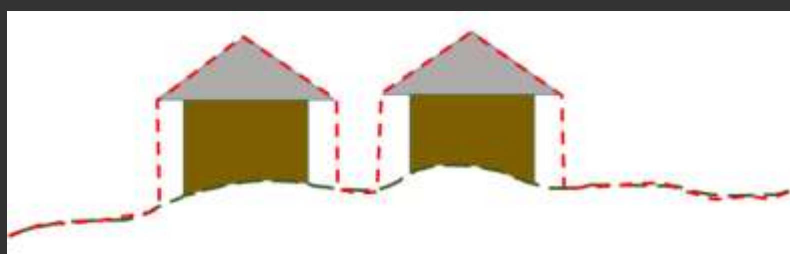
Raster-Based Elevation Data

- DTM (Digital Terrain Model) = A representation of a terrain surface calculated by measuring elevation values at a series of locations
- DEM (Digital Elevation Model) = A model of the terrain surface
- DSM (Digital Surface Model) = Ground surface + objects above the ground surface



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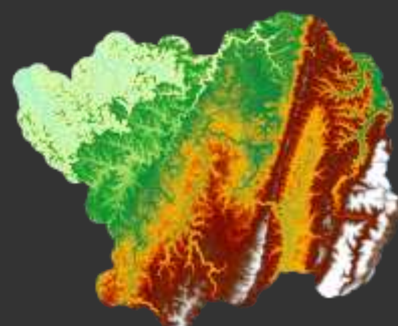
Elevation data can be represented using different geospatial data models. For example, contour lines can be used to represent elevation as isolines, where each line represents the same elevation. Individual elevation measurement can be represented as discrete point measurements. These individual point measurements can be combined as a point cloud.

For analytical purposes, it is very common to represent elevation data using raster grids where each cell holds an elevation measurement. Digital Terrain Models (DTMs) are raster-based representations of the terrain surface. In these models, above ground features have been removed, such as trees and buildings. In contrast, a digital surface model (DSM) includes aboveground features in the height surface. A digital elevation model (DEM) is a more generic term, but generally is meant to indicate a model of just the terrain surface. It is often used interchangeably with DTM.

In the provided graphic, the red line would represent a DSM surface along a transect whereas the green line would represent a DTM with the aboveground features removed.

Raster-Based Elevation Data

- DTM = A representation of a terrain surface calculated by measuring elevation values at a series of locations
- DEM = A model of the terrain surface
- DSM = Ground surface + objects above the ground surface



This is a raster model of the terrain surface.

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The images on this slide would represent a DTM since only ground elevations are included and aboveground feature have been removed. If you zoom into this surface, you will see that it is a raster where elevation measurements are stored in square cells of a defined size and spatial extent.

Normalized Digital Surface Model (nDSM)

DSM – DTM = nDSM

- Represents height of above-ground features
- When just considering trees, these are often called canopy height models
- Can be created with raster math

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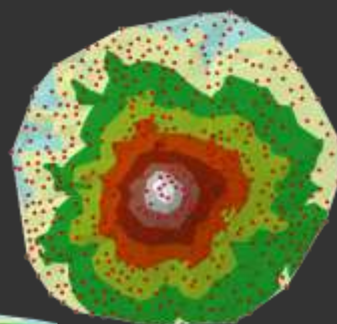
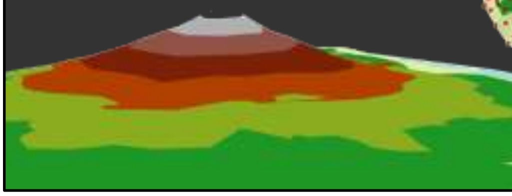
A normalized digital surface model, or nDSM, represents the height of features above the terrain surface. These surfaces are generated by subtracting a DTM from a DSM. With the ground elevations removed, the pixel values now represent the height above ground. In the example image, aboveground features include buildings and trees.

nDSMs are sometimes referred to as canopy height models. However, this term should only be used when tree canopies are the only aboveground features. In the provided image, this term would be misleading since buildings are also included in the surface.

Vector Data, Not for Discrete Features

- Triangulated Irregular Network
- Good for representing terrain data
- A space filling model

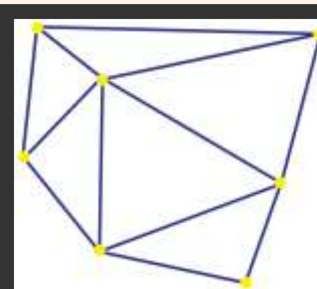




It is also possible to represent continuous variables using a vector data model as a TIN or Triangulated Irregular Network.

TINs

- ❖Connect measurement points to form a triangle (face)
- ❖Can also include contours and/or breaklines
- ❖Lines connecting points = edges
- ❖Can be used to represent a terrain (or other continuous surfaces)
- ❖Pros and cons compared to raster data



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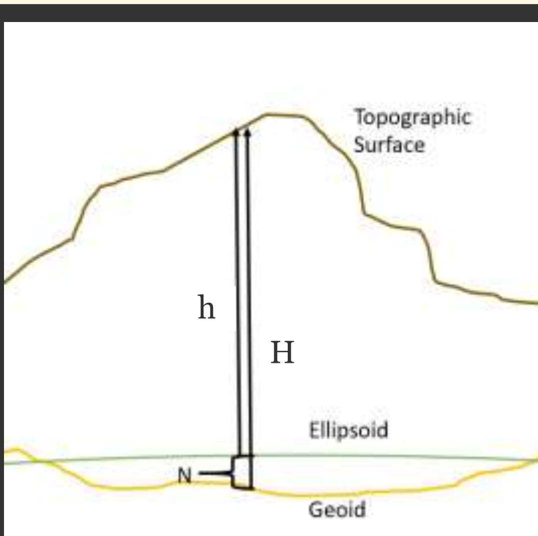
TINs are generally produced from mass points or discrete measurements. Near points are connected to form triangular faces or facets. The lines connecting the points are called edges. The triangles hold a measure derived from the connected points.

If the phenomenon of interest changes abruptly, breaklines can also be included. Breaklines represent breaks in the surface. For example, road cuts could be modeled as breaklines in a terrain surface.

There are pros and cons when representing a continuous surface as a TIN vs. a raster grid. TINs are inherently multiresolution. Smaller triangles or more detailed surfaces will be produced in areas with more point measurements whereas larger triangles or less detailed surfaces will be produced in areas with less point measurements. In contrast, a raster-based surface must have the same cell size across the entire extent. TINs can also be smaller files in comparison to raster grids, though this depends on many factors. Many of the tools available for performing terrain analysis or overlay are designed for raster data. So, it might be necessary to convert the TIN to a raster grid to undertake these analyses.

Vertical Datums



- ❖Orthometric Height (H) = height above geoid
- ❖Ellipsoidal Height (h) = height above ellipsoid
- ❖N = difference between ellipsoidal and orthometric heights

$$h = H + N$$

$$H = h - N$$

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It is importance to note that elevations can be referenced against an ellipsoid model of the earth or a geoid model. Elevations referenced to a geoid are called orthometric heights whereas those referenced against an ellipsoid are called ellipsoidal heights. N represents the difference between the orthometric and ellipsoidal heights at a location. N varies based on the location on the Earth and the orthometric and ellipsoidal models used. Sometimes the ellipsoidal height is higher than the orthometric height and sometimes the orthometric height is higher.

When comparing elevation measurements, you should make sure that either orthometric or ellipsoidal heights are used for all surfaces so that this difference does not invalidate the comparison.

LiDAR Concepts

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Components

- Laser range finder/scanner = two-way travel time between sensor and surface
- Inertial Measurement Unit (IMU) = angular orientation of the laser with respect to the ground
- GPS = locate platform and reference data relative to a datum

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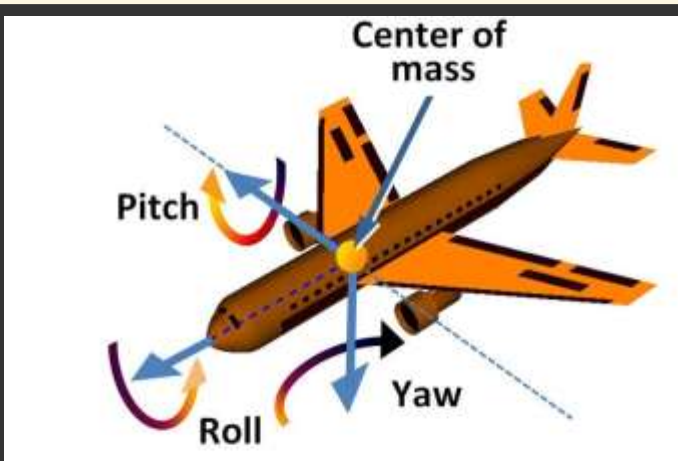
LiDAR represents elevation measurements as discrete points that are combined as a point cloud. In order to generate these data, several measures must be combined. First, a laser range finder/scanner is used to record the distance between the sensor and the surface. This device transmits EM energy as photons. These photons then travel through space. They can then strike a surface, such as the ground surface, a tree canopy, or a building, and reflect or bounce back to the sensor. The sensor records the time at which the energy was transmitted and the time at which it returned. This allows for the calculation of the two-way travel time. Since all EM radiation travels at a known speed, the speed of light, the two-way distance can be derived from travel time.

So, just using the laser data, it is only possible to estimate the distance between the sensor and the sensed object or surface. In order to actually obtain a coordinate in three-dimensional space relative to a datum, additional measurements are required. When the sensor is mounted to a moving platform, such as an airplane or drone, the motion and 3D position of the platform is recorded with an inertial measurement unit, or IMU. GPS measurements are used to obtain the precise location of the platform and sensor.

From all three data sources, accurate 3D coordinates can be obtained using geometry and trigonometry.

IMU



https://commons.wikimedia.org/wiki/File:Roll_Pitch_Yaw.JPG

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The IMU measures the 3D position and orientation of the aircraft or drone. This is required, as the position and angle of the aircraft relative to the ground impacts the travel path of the transmitted laser pulse. For example, if the aircraft roles to the side, then the pulse will be transmitted at a different angle than if the aircraft rolls at a different angle.

IMUs specifically record the pitch, yaw, and roll of the aircraft. These measures represent angles of motion relative to the 3 planes of motion, or principal axes, as extrapolated from the aircrafts center of mass.

Roll relates to rotation parallel to the long axis of the aircraft fuselage. Pitch represents rotation perpendicular to the aircraft fuselage and parallel to the orientation of the wings. Yaw is rotational motion that is both perpendicular to the long axis of the fuselage and the wings.

By measure all three rotational angles, the 3D orientation of the platform is fully described or quantified.

Travel Time to Distance

$$\text{Velocity} = \frac{Distance}{Time}$$

$$\text{Time} = \frac{Distance}{Velocity}$$

$$\text{Distance} = \text{Velocity X Time}$$

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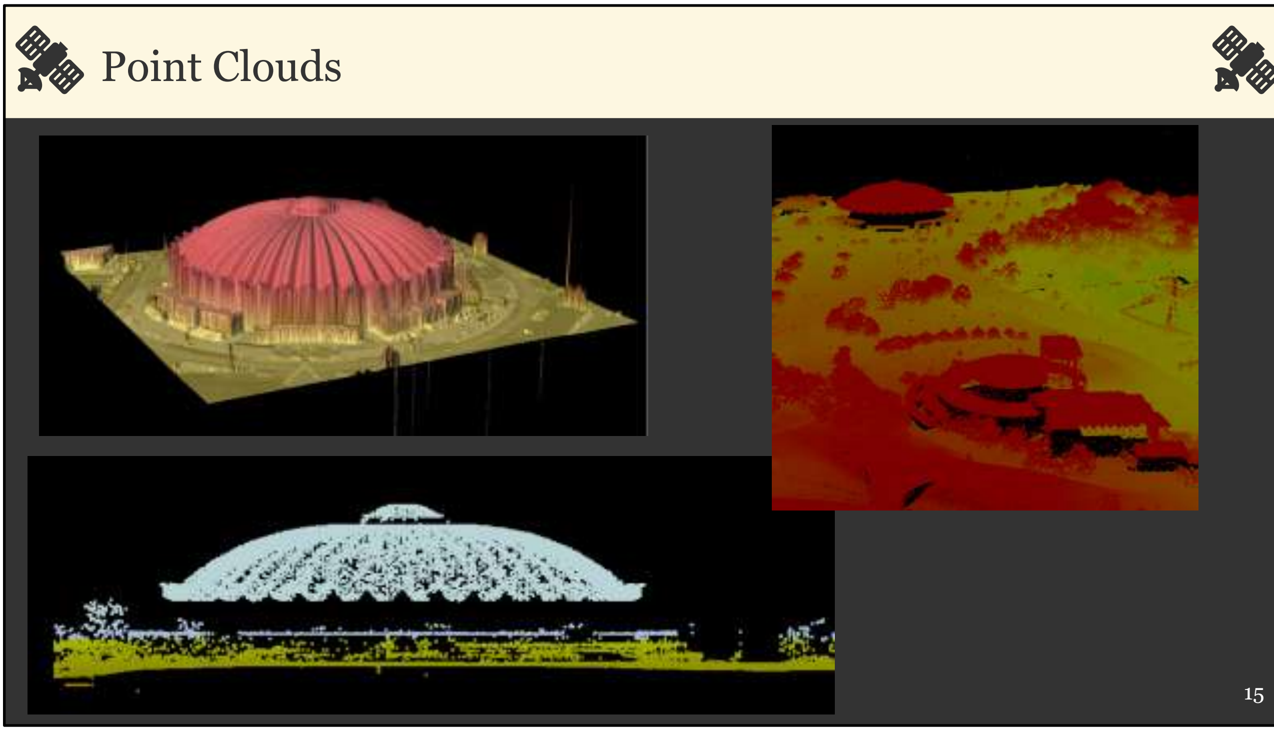
Laser scanners measure two-way travel time by differencing the time of transmission and reception of a single laser pulse. Dividing this measure by two yields travel time. Since the speed or velocity of EM radiation is a constant, the speed of light (299,792,458 m/s), travel distance can be determined from travel time.



LiDAR has a unique data structure. Instead of being stored as an array of values, or a raster grid, each 3D measurement is stored as a point measurement in 3D space. These point measurements are combined to form a point cloud. It is common for a single point cloud file to include millions or tens of millions of measurements.

The images on this slide are from a LiDAR data collection over the WVU coliseum and Creative Arts Center. Here, the data are visualized as individual points in 3D space, as a triangulated surfaces or mesh that connects the point measurements, and as a 2D transect. The level of detail and positional accuracy of these data are very impressive.

Platforms

1. Satellite
2. Airplane
3. Helicopter
4. Drone
5. Vehicle
6. Tripod
7. Phone

https://www.nasa.gov/press-release/nasa-television-to-air-launch-of-global-ice-measuring-satellite

https://www.dronezon.com/learn-about-drones-quadcopters/uav-lidar-applications-services-technology-systems/

https://en.wikipedia.org/wiki/Lidar

By Timtempleton - iPhone 6s photo, CC BY-SA 4.0, https://en.wikipedia.org/w/index.php?curid=53719003

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LiDAR sensors can be connected to a variety of platforms. In this course, we will primarily focus on data collected from an airplane platform. However, laser scanners can be connected to drones, vehicles, tripods, and satellites.

Laser scanners connected to vehicles allow for the collection of 3D, street-level models and allow spatial awareness for self-driving or autonomous vehicles.

Terrestrial laser scanners (TLS) mounted on tripods can be used to create detailed 3D models of buildings, bridges, monuments, and forest plots.

There are even lidar sensors that can be integrated into smart phones.

Data Collection and Processing

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Collecting Data (Airborne LiDAR)

- Ground GPS stations are established, or existing ground stations are used
- GPS, IMU, and laser range finding data are collected onboard the aircraft
- All areas must be covered by flight lines
- Density of points is impacted by
  - Pulse rate
  - Scan frequency
  - Flight height
  - Overlapping coverage

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In this class, we will focus on LiDAR data collected from airplane platforms because this is currently the most common method for creating DTMs over broad spatial extents.

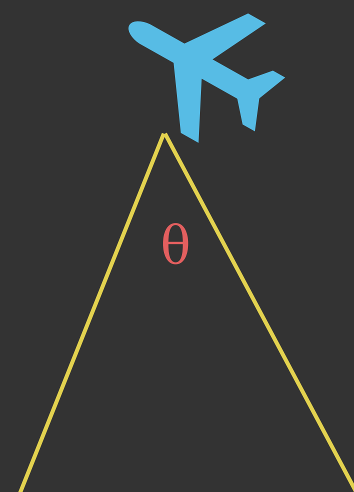
Again, obtaining accurate 3D point measurements requires data from a laser scanner, IMU, and GPS.

In order to obtain full coverage with no data gaps, pre-planned flight lines are flown, and a technician will observe the data to make sure there are no gaps between adjacent flight lines. Data gaps can result if the aircraft rolls and measurements are collected at an angle. Collecting LiDAR data is actually vary similar to mowing grass.

The density of the measurements depend on several factors, which will be discussed in the next slide.

Flight Collection Characteristics

- **Pulse Rate** = how many pulses released a second (kHz)
- **Scan Frequency** = how fast sensor scans back-and-forth (Hz)
- **Maximum Scan Angle** = maximum angle of scan (°)
- **Flight Height** = height of sensor above the ground (meters or feet)
- **Flight Speed** = average flight speed (knots)
- **Average Post Spacing** = average density of returns (points per unit area)



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Some collection characteristics relate to sensor settings. The pulse rate represents the number of laser energy pulses, or photons, transmitted per unit time. This is commonly reported in kHz (1 kHz = 1,000 pulses per second). The scan frequency relates to how many times the scanner scans back-and-forth per unit time. This is commonly reported in Hz (scans per second). The scan angle represents the maximum angle of scan relative to nadir.

Flight characteristics also have an impact, including the flight speed, which is generally reported in knots, and the flight height above the ground, which is generally reported in meters or feet.

Based on these sensor and flight characteristics, a collection can be planned that will yield a desired average post spacing, or number of returns per unit area. This is commonly reported in units of points per square meter or square foot.

Post-Processing LiDAR

1. GPS data differentially corrected
2. GPS, IMU, and laser range finder data combined to x, y, z points relative to datum
3. Raw data stored in LAS format
4. Points are classified using an algorithm
5. Manual clean up of point classification
6. Quality control and accuracy assessment
7. Creation of derived products

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Ground GPS measurements are required to correct the aircrafts GPS measurements. This generally requires the use of pre-established ground base stations. If no pre-established stations are available, the collection team will need to deploy their own ground stations that collect data throughout the entire flight mission. It is common to have at least two ground stations for redundancy and to minimize the distance from the aircraft and at least one GPS station. These data are then differentially corrected. Using the differentially correct measurements, the aircraft's GPS data can be corrected. Combining this quality GPS data with the IMU and laser range measurements allow for the calculation of 3D coordinates relative to a geospatial datum.

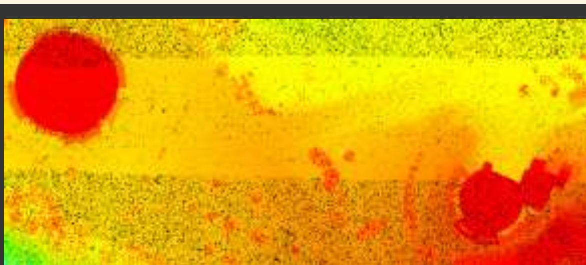
There are several file formats used to store these point clouds; however, LAS format is currently most common.

Once these 3D points clouds are generated, it is possible to further refine the data. Algorithms can be used to classify the point data; for example, it is necessary to differentiate ground returns from other returns using algorithms and additional manual editing if DTMs will be generated from the data. Currently, available ground classification algorithms cannot accurately classify or separate all ground returns. So, it is common to clean up the results using manual interpretation. This can be a very time-consuming process.

Data are also generally assessed using quality control procedures to make sure vertical and horizontal accuracy requirements are met and classifications are adequate. Positional accuracy is generally assessed by comparison to GPS measurements and the calculation of root mean square error (RMSE).

Once the point cloud has been finalized, new products and derivatives can be generated, such as 3D models or raster-based DTMs, DSMs, and/or nDSMs.

Point Attributes



- ❖Return Number = 1^{st}, 2^{nd}, 3^{rd}, 4^{th}
- ❖Classification = Unassigned, Ground, Low Vegetation, Medium Vegetation, High Vegetation, etc.
- ❖Return Intensity = measure of amount of energy returning to sensor
- ❖RGB values = assign image RGB values to points

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Many LiDAR sensors are capable of recording more than just the 3D coordinates of the laser pulse.

It is common for discrete return sensors to be able to record more than one return from each laser pulse. For example, if a laser pulse intersects a forest canopy, a portion of the energy can reflect or bounce back from the top of the canopy while the remaining energy continues to propagate. This allows for subsequent returns to be collected representing subcanopy features or even the ground surface. It is common for up to 4 returns per laser pulse to be recorded. This characteristic of LiDAR allows for ground returns under a forest canopy and a partial characterization of canopy structure.

Following post-processing, it is possible to assign classification codes to each point. These are generally derived by a combination of automated classification algorithms and manual editing.

The intensity of the returned laser pulse is also commonly recorded. When a laser pulse strikes a surface, some of the energy may be absorbed while some is reflected. When multiple returns are collected, the total energy will be split amongst multiple returns.

Lastly, if imagery is collected along with the point cloud data, RGB values can be associated with each laser return.

Return Intensity

- Correlates with:
  - Return number
  - Surface material
  - Moisture level

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Return intensity of the laser pulse is impacted by many factors including the number of returns, the surface material, and the moisture content. The provided image shows a large number of points symbolized using return intensity. Darker shades indicate a lower return intensity while brighter areas indicate more return intensity. These data were collected with an infrared laser.

Grass and low vegetation tend to show a high return intensity since there is no vertical structure to break the pulse into multiple returns and because vegetation tends to reflect NIR radiation. In contrast, paved surfaces tend to absorb NIR radiation and are dark in the image.

Forests tend to show a mixture or texture of high and low return intensities. This is because vegetation tends to reflect NIR radiation. However, due to vertical structure, a single pulse is often broken into multiple returns.

Although not represented in this example, water tends to absorb a large amount of NIR radiation and will show low return intensity or no returns, as it may absorb all the energy.

These data can be useful for data visualization and as input to classification routines. However, it should be noted that return intensity has been shown to be hard to calibrate. So, it is difficult to use these measurement in a quantitative manner. For example, it would be difficult to convert return intensity to NIR surface reflectance.

RGB/RGBN Encoding

- Can encode points with values from an image
- RGB or RGBN
- Can symbolize using the codes

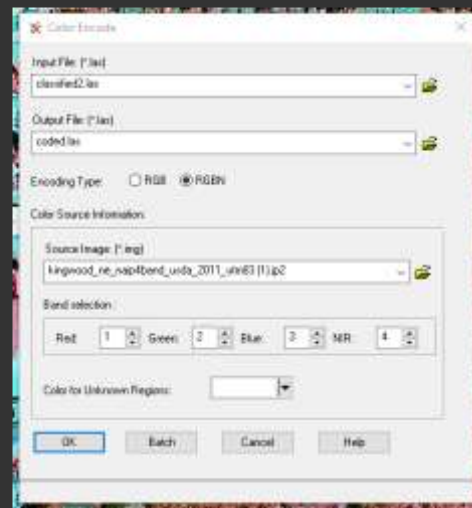

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Image data can be associated with each point in the point cloud if the datasets spatially co-occur. Sometimes imagery are collected alongside LiDAR. Alternatively, data collected at a different time can also be used, as long as temporal misalignment is not a concern.

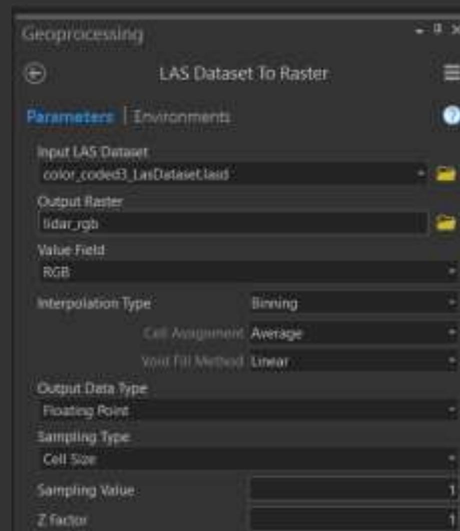
It is possible to extract RGB values or RGB and NIR values, depending on the imagery available.

These measurements can be misleading due to differences in spatial resolution. Also, subcanopy returns will be assigned DN values representing the top of the canopy, since the imagery does not penetrate the canopy. Essentially, the DN values are extracted based only on the 2D point and image coordinates. Another issue is that images often contain vertical relief displacement whereas LiDAR data do not. So, this can lead to further misalignments.

Despite, these limitations, attaching RGB values to points clouds can be useful. The image provided on this slide shows a CIR symbology of point features.

Encoded RGB to Raster

❖Can convert RGB values stored on points to a multiband raster



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In this slide, I have converted the point data to a multiband raster using the RGB values, essentially recreating a raster image from the point measurements.

LAS Classification Codes

Classification Value	Meaning
0	Never classified
1	Unassigned
2	Ground
3	Low Vegetation
4	Medium Vegetation
5	High Vegetation
6	Building
7	Low Point
8	Reserved
9	Water
10	Rail

Classification Value	Meaning
11	Road Surface
12	Reserved
13	Wire - Guard (Shield)
14	Wire - Conductor (Phase)
15	Transmission Tower
16	Wire-Structure Connector (Insulator)
17	Bridge Deck
18	High Noise
19-63	Reserved
64-255	User Definable

http://desktop.arcgis.com/en/arcmap/10.3/manage-data/las-dataset/lidar-point-classification.htm

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LAS files have defined, standard classification codes, as described in the provided tables. Generally, ground points are assigned a value of 2. If only ground points are differentiated, all other points will be coded to 1, or unassigned, or labelled as an outlier, generally using code 7 or 18. Codes have been defined for vegetation based on height, buildings, water, rails, roads, wires, transmission towers, and bridge decks. Some codes are reserved for special use, and analysts can use remaining codes to define user-specific classes. This coding scheme uses 8-bit encoding, so 256 values are available.

LAS Class Flags

- Provide a secondary description or classification for LiDAR points

http://desktop.arcgis.com/en/arcmap/10.3/manage-data/las-dataset/lidar-point-classification.htm

Field Name	Description
Synthetic	A point that was created by a method other than lidar collection, such as digitized from a photogrammetric stereo model.
Key-point	A point considered to be a model key-point and should not be withheld in any thinning algorithm.
Withheld	The point should not be included in processing.
Overlap	A point that is within the overlap region of two or more flight lines or swaths (LAS version 1.4 specific).

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Class flags can also be assigned to specific points. For example, synthetic points are those not created by the LiDAR collection, such as those manually added or obtained using photogrammetric methods. The key-point flag is used to note that a point is important and should not be removed by any thinning process. For example, points near a slope break may be flagged as key-points so that the steep slope is well represented even if the data are thinned. The withheld flag is used to make sure that points are not included in subsequent processing or analysis. For example, outlier points could be flagged this way. Lastly, the overlap flag can be used to indicate points that occur in areas of overlapping flight lines.

Types of Systems

- Land
  - Near-Infrared laser
- Water
  - Blue/Green (Infrared has few returns over water)
  - Depth penetration depends on clarity
  - 3-4x depth you can see with naked eye

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It is common for NIR wavelengths to be used when collecting LiDAR over land surfaces. When collecting data over water and when some penetration is desired, such as for bathymetric mapping, NIR lasers are commonly avoided, since water tends to absorb a large proportion of these wavelengths. In fact, it is common to receive no NIR laser returns from water since all the energy is absorbed. Instead, a blue/green laser can be used which can generally penetrate 3 to 4 times the depth viewable with the naked eye. This depends on water clarity, with reduced clarity yielding less penetration.

Types of Systems

- Discrete Return = records returns as discrete measurements (potentially multiple returns per laser pulse)
- Flash = records depth and intensity as array of pixels
- Full Waveform = record as full waveform of return intensity
- Geiger = low energy pulses at high repetition rate
- Multispectral = uses multiple lasers with different wavelengths

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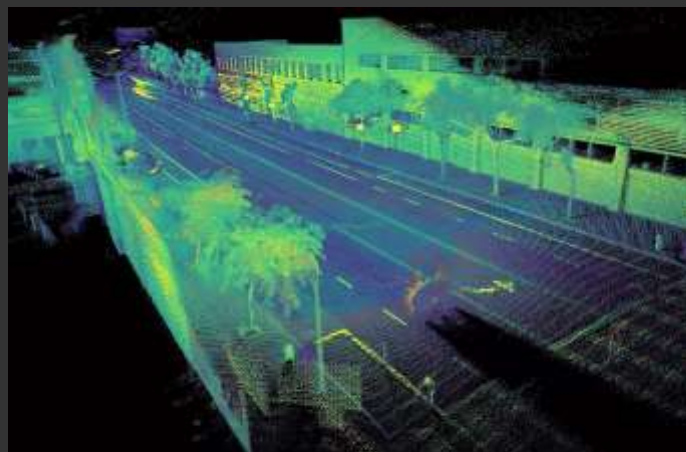
There are also different types of LiDAR systems. In this class, we focus on discrete return systems specifically, since they are currently the most commonly used systems for large-area terrain mapping.

Flash lidar releases a single flash of multiple laser pulses at once that are used to generate a data array that records depth (i.e., distance) and intensity measurements. These systems tend to be cheaper than discrete, multiple return systems and are commonly used in self-driving cars.

Full waveform LiDAR returns a full waveform of return intensity signals as opposed to discrete returns. Geiger LiDAR relies on low energy pulses transmitted at a high repetition rate and can yield vary detailed data.

Lastly, multispectral LiDAR uses multiple laser pulses at different wavelengths.

Flash LiDAR



https://ouster.com/blog/how-multi-beam-flash-lidar-works/

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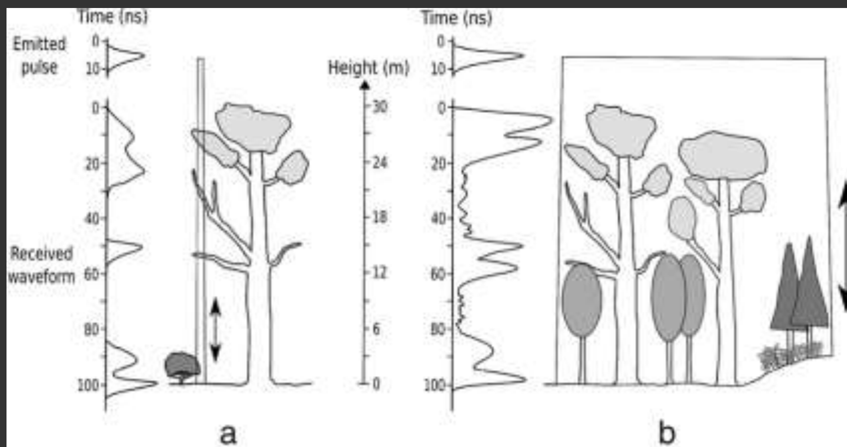
This image provides an example of flash LiDAR collected at street level. Again, these systems can generally record both return intensity and distance.

Full Waveform LiDAR

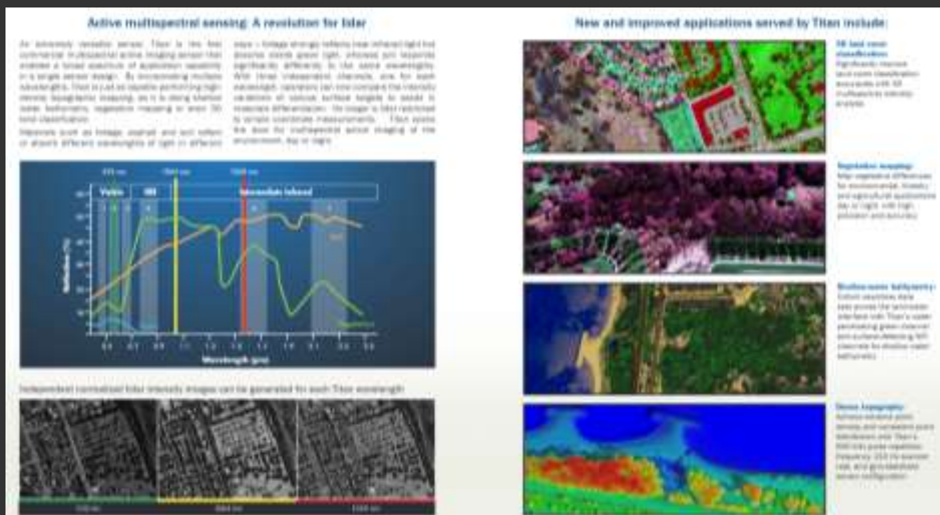


Mallet, C. and Bretar, F., 2009. Full-waveform topographic lidar: State-of-the-art. *ISPRS Journal of photogrammetry and remote sensing*, *64*(1), pp.1-16.

30

The image on this slide describes the difference between discrete return LiDAR (a) and full waveform LiDAR (b). In the conceptualized forest with vertical structure, the discrete return sensor records three discrete returns associated with a single laser pulse. In contrast, The full waveform LiDAR records the complete energy signature of the return. From this raw waveform data, it is possible to generate derivatives to characterize vertical canopy structure.

Multispectral LiDAR



https://geo-matching.com/uploads/default/m/i/migrationjkz5ct.PDF

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Multispectral LiDAR transmits multiple laser pulses at different wavelengths. The sensor described on the image provided on this slide collects data using green, NIR, and SWIR lasers. These data can be combined to generate false-color composites along with characterizing the terrain surface and vertical landscape structure. Again, in contrast to imagery, LiDAR does not suffer from vertical relief displacement. So, multispectral LiDAR can be used to interpolate false-color images without any vertical relief displacement. Such data are valuable as input to feature extraction and classification tasks. Unfortunately, such data are not currently widely available.

Sources of Error

1. Equipment/signal error
2. Lack of ground points
3. Multipath
4. Non-ground objects
5. Bad processing

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Sources of error in LiDAR data can result from issues with the equipment, including the GPS receivers, laser scanners, and IMU. It is important to keep all equipment well-calibrated and serviced.

If vegetation cover is very thick, then there may be a lack of ground returns in these areas, resulting in terrain models that poorly characterize the sub-canopy ground surface.

Multipath issues can artificially lengthen travel time and result in outlier measurements. Multipath error occurs when a laser pulses bounces off multiple surfaces. For example, a pulse could bounce off the ground, then a building, and then another building before returning to the senor. It is even possible for photons to pass through windows and bounce around rooms before reflecting back out of the building and returning to the sensor.

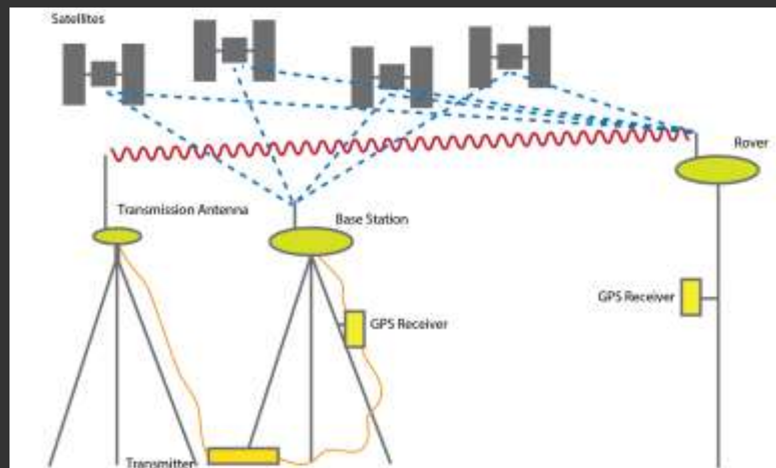
Sometimes, non-ground features may fail to be removed from the terrain surface. Also, what actually constitutes “ground” is not always clear. For example, should boulders sitting on the landscape be included as part of the ground or removed? If you ask a geomorphologist, he or she would likely say yes, since these boulders are a key characteristic of the landscape. However, a hydrologist may want these features excluded since they may hinder the generation of surface flow models.

Issues in data processing can also be a cause of error. Specifically, this could include poor processing of the GPS data, a poorly defined ground return classification algorithm, or inadequate manual clean up.

Lastly, there are other odd sources of error. For example, it is possible to record returns from birds in flight, which would result in a high outlying point.

Accuracy Assessment

- Visual inspection
- Comparison to more accurate data: post-processed GPS or RTK GPS
- Assess x, y, z measurements using RMSE



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All datasets have some error or uncertainty. In order to assess the positional error of LiDAR data, it is common to use high quality GPS measurements that are assumed to be of greater accuracy than the LiDAR data. For example, ground measurements can be collected using Real Time Kinematic (RTK) GPS surveys. These measurements can then be compared to the nearest LiDAR point measurements to calculate RMSE in the horizontal and vertical directions.

Generally, LiDAR data have a very high positional accuracy, with error in the horizontal and vertical directions on the scale of centimeters or even millimeters.

LiDAR Visualization and Measurement

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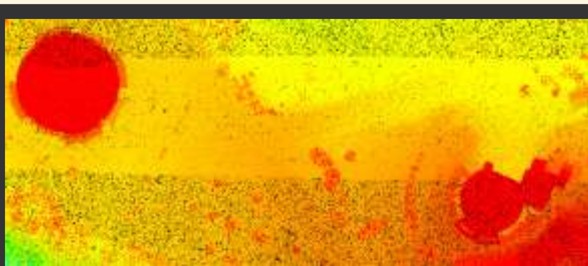
Visualizing Variables



- ❖Elevation
- ❖Intensity
- ❖Classification
- ❖Source file
- ❖Last/Intermediate/First returns
- ❖Return Number

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In this section, we explore means to view or symbolize LiDAR point clouds. I mainly show examples from ERDAS Imagine.

It is common to symbolized data based on elevation (the top image on the page), return intensity, classification (ground, low vegetation, medium vegetation, high vegetation, etc.), and return number (1 through the maximum number of recorded returns).

You can also differentiate last returns from multiple returns, first returns from multiple returns, intermediate returns from multiple returns, or single returns.

You can also change the size of the point symbol representing each return.

Viewing LiDAR

- ❖Can change color coding
- ❖Can change z-factor
- ❖Can change point size
- ❖Can change color ramp

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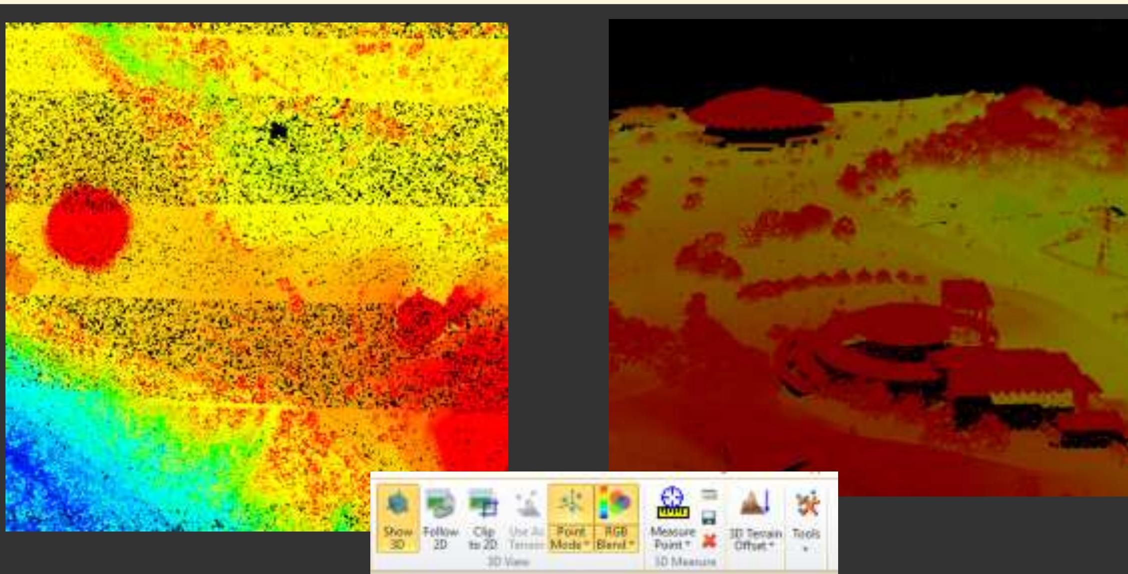
In 2D or planar view, you can change the color coding when representing categories (such as classification), set a z-factor to adjust the vertical scale relative to the horizontal, change the color ramp used to show continuous data (such as elevation or return intensity), and change the size of each point.

2D and 3D



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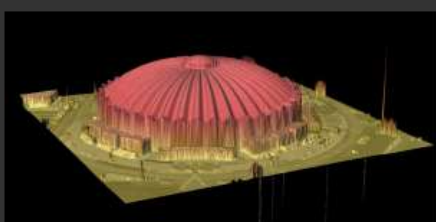
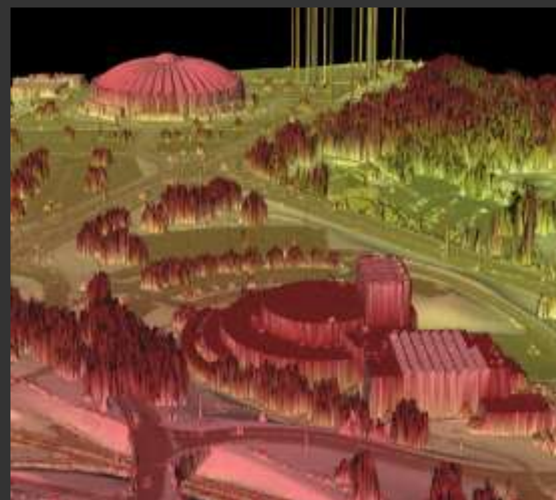
This slide compares 2D plan view and 3D view representations of LiDAR data. In both images color codes represent elevation.

More on 3D Viewing

- Can change point symbology
- Can link 2D and 3D views
- RGB and Intensity Blends
- Can clip to the extent of the 2D view





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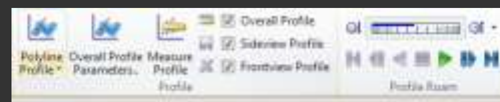
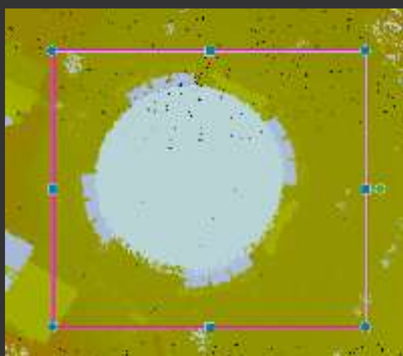
It is sometimes possible to link 2D and 3D views so that the scale and/or extent remain the same as you move within either view. In Erdas Imagine, it is possible to clip the viewing extent of a 3D view to the extent of a 2D view.

Instead of symbolizing using individual points, it is possible to apply drapes or TINs to create a continuous 3D surface.

Profiles

- Can create profiles within rectangular extents
- Can create profiles along lines





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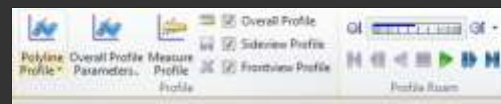
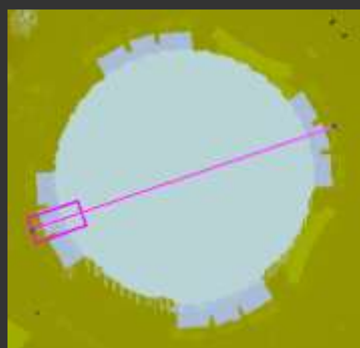
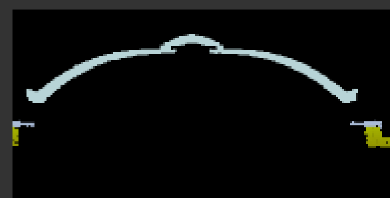
It is also generally possible to generate 2D profiles within rectangular extents or along lines. The example profile on the right was generated for the rectangular extent defined on the left.

Profiles

- ❖Can create profiles within rectangular extents
- ❖Can create profiles along lines







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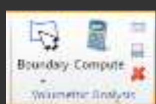
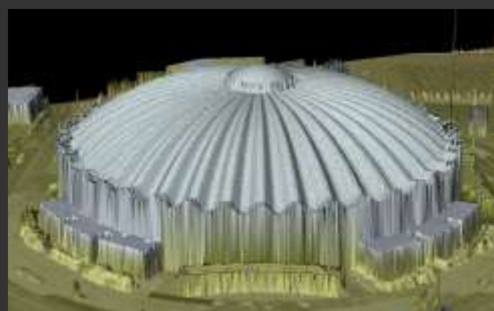
This profile was generated along a line with a defined width to capture more data points.

Volumetric Analysis

- Can save measurements to a text file





2D View #1 Volumetric Analysis Summary

Row	Length	Area	Cut	Fill	Total Volume
1	2046.7	145714.5	7725060.6	40834.3	-7685226.3

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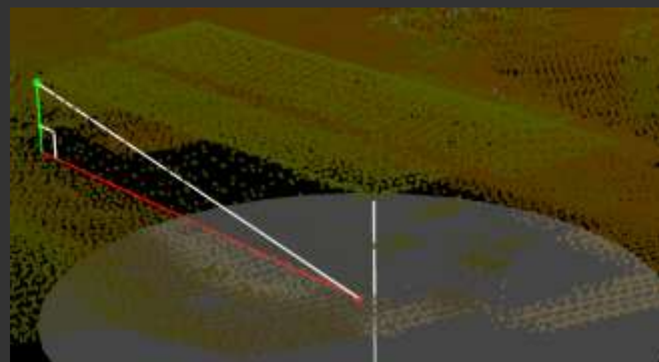
It is also possible to calculate or estimate 3D volumes. This can be valuable for assessing change or taking inventories. For example, coal piles could be inventoried on different dates to assess the amount of coal that has been moved, used, or sold.

Measurements in 3D

- Measure Point
- Measure Line
- Measure Surface



Can save measurements to a text file

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Since these data are 3D, it is possible to make measurements of points, lines, and surfaces in 3D space.

LiDAR Rasterization

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Surface Examples

Intensity

DTM

DSM

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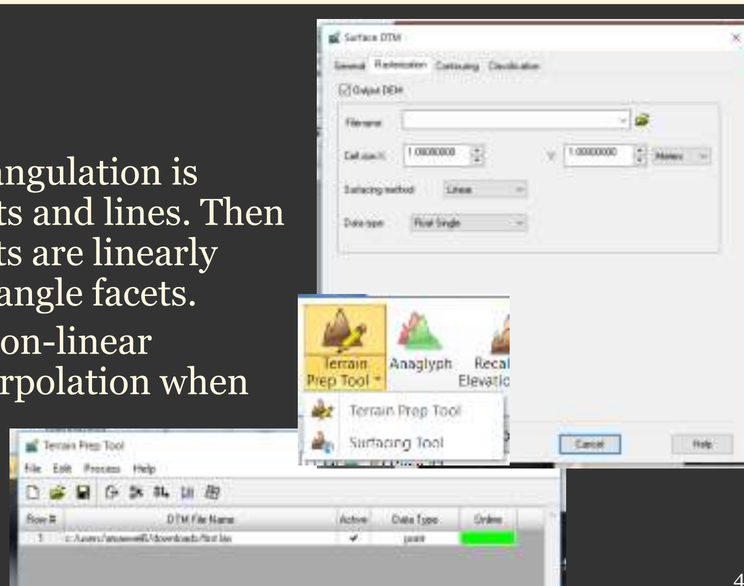
It is common to interpolate raster surfaces from LiDAR point measurements to create continuous surfaces that can be more easily integrated into subsequent analyses. Common surfaces include intensity images, DTMs, and DSMs. Once DTMs and DSMs are generated, it is possible to difference them to obtain raster-based nDSMs.

Rasterizing LiDAR in Erdas Imagine

- Use Terrain Prep Tools
- Surfacing Methods
  - Linear = A Delaunay triangulation is created using input points and lines. Then the Z values of DEM posts are linearly interpolated from the triangle facets.
  - Non-Linear = Perform non-linear (smooth and round) interpolation when generating the surface.



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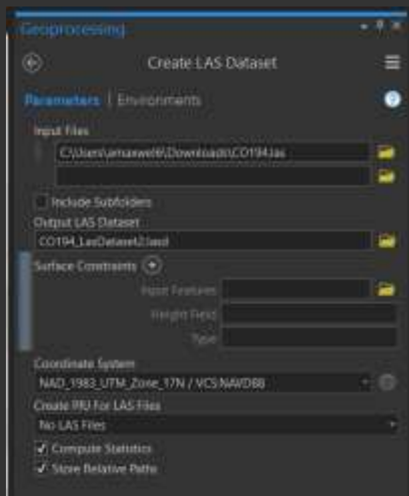
LiDAR point cloud rasterization can be accomplished in Erdas Imagine using the Terrain Prep Tools. These tool provide two interpolation methods. Linear uses Delaunay triangulation to create a TIN surface. The raster data are then interpolated from the triangular facets making up the TIN. The Non-Linear method incorporates smoothing and rounding into the rasterization process.

Rasterize LiDAR in ArcGIS Pro



❖ LAS data must be converted to a LAS Dataset

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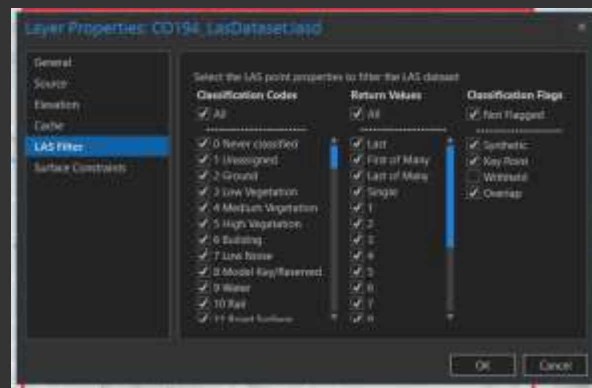
In ArcGIS Pro, point clouds in LAS format must first be converted to LAS Datasets. A LAS Dataset is similar to a mosaic dataset: it is not a new dataset, but a reference to a set of multiple files, in this case multiple LAS files. LAS Datasets can then serve as input to subsequent processing and analysis.

Rasterize LiDAR in ArcGIS Pro

- Data must be filtered to obtain the desired product
- Can filter by class, return number, and/or classification flags



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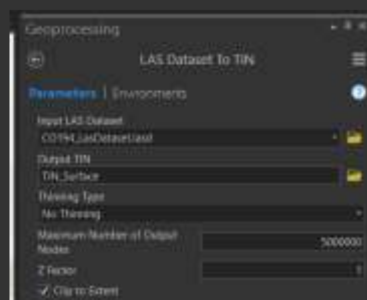
In ArcGIS Pro, filters can also be defined. These filters are honored in subsequent processing. For example, if a DTM raster grid is to be produced, all non-ground points can be filtered out so that only the classified ground returns are used in the subsequent rasterization.

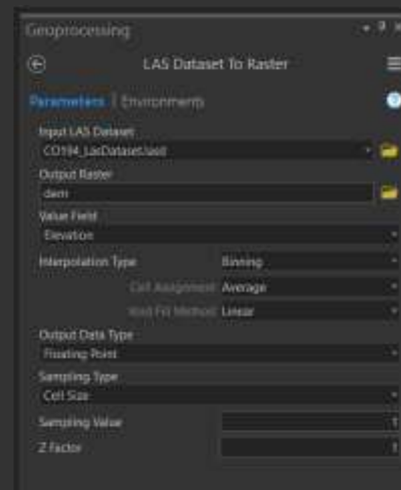
You can filter based on classification, assuming that the point cloud has been classified, return number, and/or classification flags.

Last returns are single returns or last of multiple returns. First of Many means the first of multiple returns. Last of Many indicates the last of many returns and does not include single returns. Lastly, single returns does not include returns associated with multiple returns from a single pulse.

Rasterize LiDAR in ArcGIS Pro

- ❖Create raster surface using LAS Dataset to Raster Tool
- ❖Can Convert to TIN using LAS Dataset to TIN Tool





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There are a couple of rasterization options in ArcGIS Pro. The LAS Dataset to Raster tool allows for a raster grid to be generated from a point cloud using some predefined methods. Alternatively, point clouds can be converted to a TIN surface. TIN surfaces can be rasterized after they are created.

Rasterize LiDAR in ArcGIS Pro

- Interpolation Methods
  - Binning = cell is assigned a statistic from the points that fall inside of it: average, minimum, maximum, IDW, nearest
  - Triangulation = calculate a cell based by rasterizing a TIN generated from the point cloud
- Void filling
  - Linear = linear interpolation across voids
  - Natural Neighbor = uses natural neighbor interpolation
  - Simple = averages the values from data cells immediately surrounding a NoData cell
  - None = voids are not filled

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The LAS Dataset to Raster Tool in ArcGIS Pro provides two interpolation methods: binning and triangulation. Binning calculates a statistic from the filtered points that occur within each cell extent to assign a value to each cell. This measure can be the average, minimum, or maximum. IDW will generate an inverse-distance weighted average where returns near the center of the cell are weighted higher than those toward the margins. Nearest will simply use the return nearest to the center of the cell and ignore all other returns. The second method, triangulation, involves generating a TIN surface from the point cloud and then rasterizing the triangular facets.

If cells do not have any returns that occur within them, then voids will exist in the raster datasets. A couple options are available for filling these voids. First, linear interpolation can be used to fill the voids by linearly interpolating raster cell values on the margins of the gap. In contrast, nearest neighbor only considers the nearest cell value while simple will average all cells that touch or immediately surround the gap.

If you do not want to fill the voids, then they can be assigned a NoData value.

When I create a DTM, I tend to use the binning method, the average of the points within the cell, linear void filling, and filter to just use the ground classified points. To create a DSM, I tend to use the same settings other than replacing the average cell value with the maximum and using a first returns or single returns filter.

To interpolate a raster grid from intensity data, I tend to using the binning method, the average of the point intensity values within the cell, and no void filling. This is because voids may occur as a result of full absorption of the laser pulse. For example, it is common for all NIR energy to be absorbed by water. So, there are likely to be gaps over rivers and ponds. I then recode these cells to 0, based on the assumption of full absorption. To rasterize the intensity of the first returns only, you will want to apply a filter so that only single returns or first of many returns are included.

LiDAR Applications

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Uses

1. 3D visualization
2. Urban mapping
3. Utility line mapping
4. Geomorphology
5. Hydrology
6. Archeology
7. Landscape architecture
8. Surveying
9. Self-driving cars
10. Etc.

https://www.ted.com/talks/sarah_parcak_archeology_from_space

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There are many uses of LiDAR data, and the applications continue to expand with time due to adoption of new techniques, development of new technologies, and reduced cost of sensors. This slide lists some fields that commonly use LiDAR technologies. We will explore some specific examples in the following slides.

Video: LiDAR in Archeology

https://youtu.be/YFC5CwZVCEw?si=WXdF3TFwSPDAFw6_

Video from TED

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Forestry

- Forest structure
- Tree crown delineation
- Tree speciation
- Biomass
- Fuel loads

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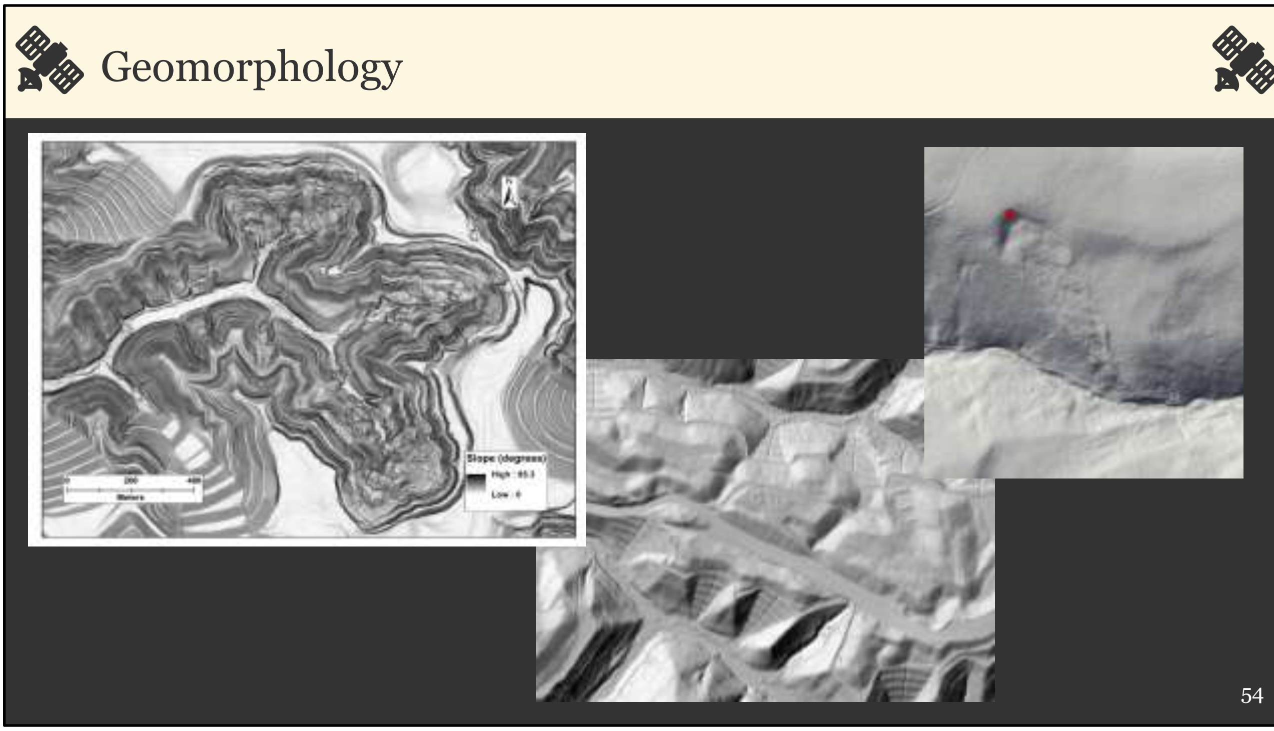
Foresters use LiDAR to characterize the 3D structure of forests. Such data can be used to assess the amount of biomass present in a forest stand or plot and also the fire fuel load, which can be used for fire management. The use of LiDAR to delineate tree crowns and classify tree species is still an active area of research.

A related application is utilities management. For example, LiDAR data can be used to assess power lines to determine if lines are sagging or vegetation is encroaching on the right-of-way.



Geomorphologists use LiDAR to delineate landscape features, assess landscape changes, and identify geohazards.

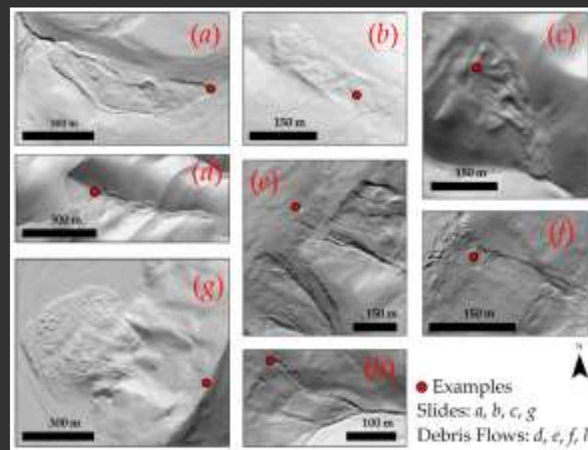
The left image on this slide represents a slopeshade of a surface mine complex. Valley fills ring the flatten mountaintop and some slope instability is noted in the adjacent valleys. The middle image shows a hillshade representation of a mine site characterized by flattened mountaintops and filled valleys. Modern, high spatial resolution digital terrain data are of great value in understanding anthropogenic impacts on the landscape.

The image on the right shows a landslide or slope failure. The red dot indicates the position of the head scarp.

Geohazards

https://www.mapwv.gov/flood/map/

Maxwell, A.E.; Sharma, M.; Kite, J.S.; Donaldson, K.A.; Thompson, J.A.; Bell, M.L.; Maynard, S.M. Slope Failure Prediction Using Random Forest Machine Learning and LiDAR in an Eroded Folded Mountain Belt. *Remote Sens.* **2020**, *12*, 486.



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At the West Virginia GIS Technical Center, we have been using LiDAR data to assess geohazards across the state. The quality of these data have allowed us to update floodplain maps and generate models to assess the likelihood of slope failure, or landslide, occurrence. Both of these projects would not be possible without LiDAR data.

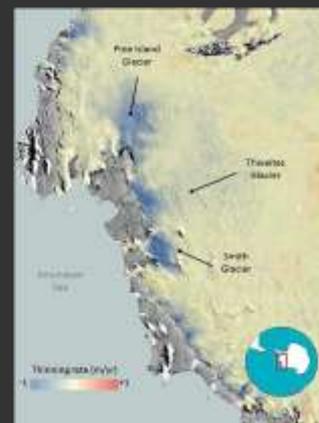
Monitoring the Cryosphere

- NASA
  - ICESat
  - ICESat-2
- ESA
  - Cryosat
  - Cryosat-2

ICESat-2

ICE, CLOUD, AND LAND ELEVATION SATELLITE-2

https://icesat-2.gsfc.nasa.gov/



https://earth.esa.int/web/eoportal/satellite-missions/c-missions/cryosat-2

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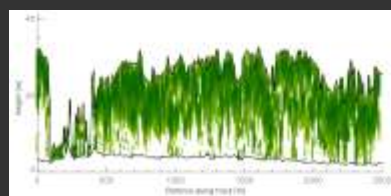
LiDAR data are also of value for monitoring the cryosphere, which is of extreme importance due to global climate change. THE NASA ICESat and ICESat-2 missions, along with the European Space Agency's (ESA) Cryosat and Cryosat-2 missions, allow for regular monitoring of Artic and Antarctic ice extents. Using multi-temporal data, it is possible to estimate changes in ice height and volume. With a longer time series, it is possible to estimate thinning rates.

Global Forest and Carbon Monitoring

- Global Ecosystem Dynamics Investigation
- International Space Station (ISS)
- Carbon sequestration
- Forest height and vertical structure
- Forest canopy characteristics
- Deforestation



ATBD #	Data products	Product leads	Resolution
L1A-2A	1A: Raw waveforms, 2A: Ground elevation, canopy top height, relative height (RH) metrics	Michelle Hofton, Bryan Blair	25 m (~82 ft) diameter
L1B	Geolocated waveforms	Scott Luthcke, Tim Rebold, Taylor Thomas, Teresa Pennington	25 m (~82 ft) diameter
L2B	Canopy Cover Fraction (CCF), CCF profile, Leaf Area Index (LAI), LAI profile	Hao Tang, John Armston	25 m (~82 ft) diameter
L3	Gridded Level 2 metrics	Scott Luthcke, Terence Sabaka, Sandra Preaux	1 km (~0.6 mi) grid
L4A	Footprint level above ground biomass	Jim Kellner, Laura Duncanson, John Armston	25 m (~82 ft) diameter
L4B	Gridded Above Ground Biomass Density (AGBD)	Sean Healey, Paul Patterson	1 km (~0.6 mi) grid
Demonstrative products	Prognostic ecosystem model outputs	George Hurtt	Grid size: Variable
Demonstrative products	Enhanced height/biomass using fusion with TanDEM-X	Lola Fatoyinbo, Seung-Kuk Lee	Grid size: Variable
Demonstrative products	Enhanced height/biomass and biomass change using fusion with Landsat	Matt Hansen, Chengquan Huang	Grid size: Variable
Demonstrative products	Biodiversity/habitat model outputs	Scott Goetz, Patrick Jantz, Pat Burns	Grid size: Variable

https://gedi.umd.edu/

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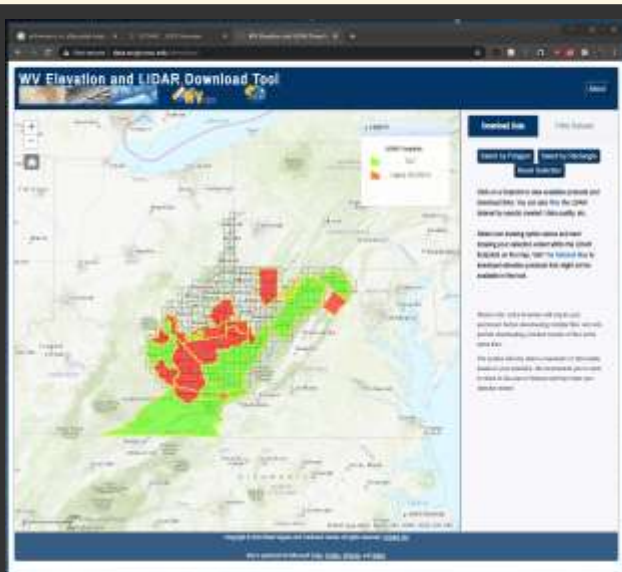
The Global Ecosystem Dynamics Investigation (GEDI), which is operated from the International Space Station (ISS), uses full waveform LiDAR to collect forest height and vertical structure data. These data are used to model forest canopy characteristics, assess the amount of carbon sequestered in forests, and map forest change and deforestation. This is currently the highest spatial resolution LiDAR sensor operating from a space platform. The resolution of the derived data products range from 25 meters to 1 kilometer.

LiDAR in West Virginia



http://data.wvgis.wvu.edu/elevation/

Public LiDAR data that have been collected across the state of West Virginia can be downloaded free-of-charge using the WV Elevation and LiDAR Download Tool web app. This tool is maintained by the West Virginia GIS Technical Center and West Virginia View.

USGS 3DEP Program

- Free elevation data download
- Draws from a variety of data sources
- A replacement for the National Elevation Dataset (NED)
- This is still developing

https://nationalmap.gov/3DEP/

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The 3DEP Program in the United States is working toward high spatial resolution, predominantly LiDAR-derived elevation data for the entire country. Interferometric Synthetic Aperture RaDAR, or IfSAR, data will be collected over Alaska.

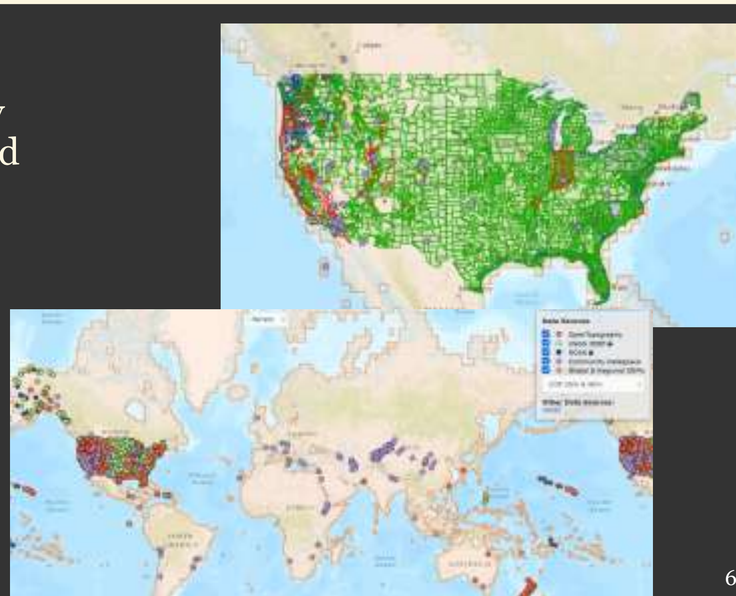
This program is ongoing, but nationwide coverage is expected soon.

This program highlights the practical value of LiDAR data.

OpenTopography

OpenTopography
High-Resolution Topography Data and Tools

- NSF-funded
- Provides access to a variety of lidar datasets and derived products
- Additional access for researchers and students
- Download or access programmatically
- Includes processing and analytics tools



https://opentopography.org/

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The OpenTopography program is another great source of LiDAR data.

LiDAR Tools

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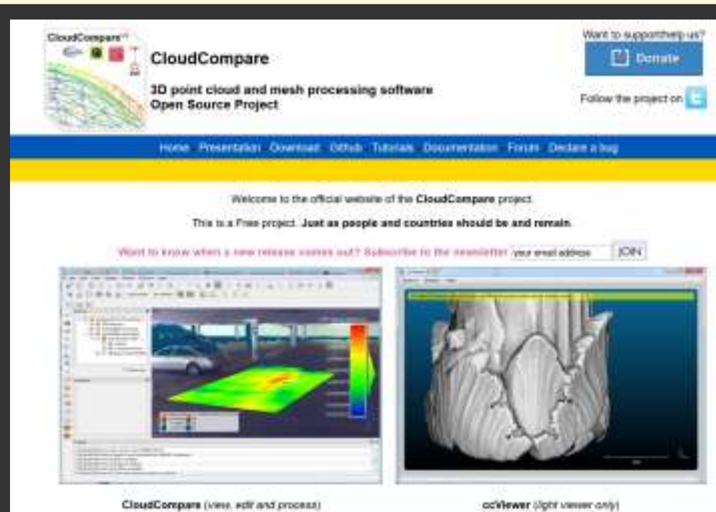
CloudCompare

- Free
- View and work with point clouds



https://www.cloudcompare.org/

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LiDAR data and other point clouds can be viewed and worked with using the free CloudCompare software tool.

R


The lidR package

1 Introduction

https://github.com/r-lidar/lidR
https://r-lidar.github.io/lidRbook/

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The lidR package allows for working with and processing LiDAR data and point clouds in the R data science environment.

Python


Project description

Welcome to the lidar package

lidar is Python package for delineating the nested hierarchy of surface depressions in digital elevation models (DEMs). It is particularly useful for analyzing high-resolution topographic data, such as DEMs derived from Light Detection and Ranging (LiDAR) data.

- GitHub repo: https://github.com/giswqs/lidar
- Documentation: https://lidar.gishub.org
- PyPI: https://pypi.org/project/lidar
- Conda-forge: https://anaconda.org/conda-forge/lidar
- Open in Colab: https://gishub.org/lidar-colab
- Free software: MIT license

Citations:

- Wu, Q., (2021). lidar: A Python package for delineating nested surface depressions from digital elevation data. *Journal of Open Source Software*, 6(59), 2965. https://doi.org/10.21105/joss.02965
- Wu, Q., Lane, C.R., Wang, L., Vanderhoof, M.K., Christensen, J.R., & Liu, H. (2019). Efficient Delineation of Nested Depression Hierarchy in Digital Elevation Models for Hydrological Analysis Using Level-Set Method. *Journal of the American Water Resources Association*. https://doi.org/10.1111/1752-1688.12689 (PDF)

Contents:

- Introduction
- Statement of Need

https://pypi.org/project/lidar/

The lidar library allows for working with LiDAR using the Python environment and language.

This is the end of this lecture module.

Please return to the West Virginia View Webpage for additional content.

Thanks! Hope you found this useful.