Appendix C – Frequently Asked Questions (FAQs)

The Florida Statewide LiDAR Assessment, including the questionnaire to be completed by Florida LiDAR stakeholders and users, is our attempt to identify Florida's requirements for and benefits of statewide topographic, bathymetric and topobathymetric LiDAR. A statewide LiDAR acquisition plan is a moving target, with federal, regional, and local governments moving forward in some cases with individual, uncoordinated efforts, consistently changing the picture of available data. LiDAR technologies are rapidly changing – with new equipment and techniques frequently available to produce higher quality data should adhere to the following strategic principles:

- **Large, seamless, temporally consistent areas should be prioritized.** A persistent issue with existing high-resolution digital elevation data across the State of Florida are inconsistent elevations between existing projects which may have been collected under different seasonal conditions and years apart. Larger acquisition areas decrease these seams, minimizing inconsistencies.

  For scheduling LiDAR data acquisitions, existing aerial photography 3-year flight schedule should be considered. Florida Department of Revenue coordinates the capture and distribution of high-resolution aerial photographs of approximately one third of the state each year according to the provisions of 195.022, FS. Improvement in the quality and value of both LiDAR and aerial photographs will occur when collected near the same time and under similar environmental conditions. LiDAR data collection should consider the existing aerial photography 3-year flight schedule (see Figure 1).

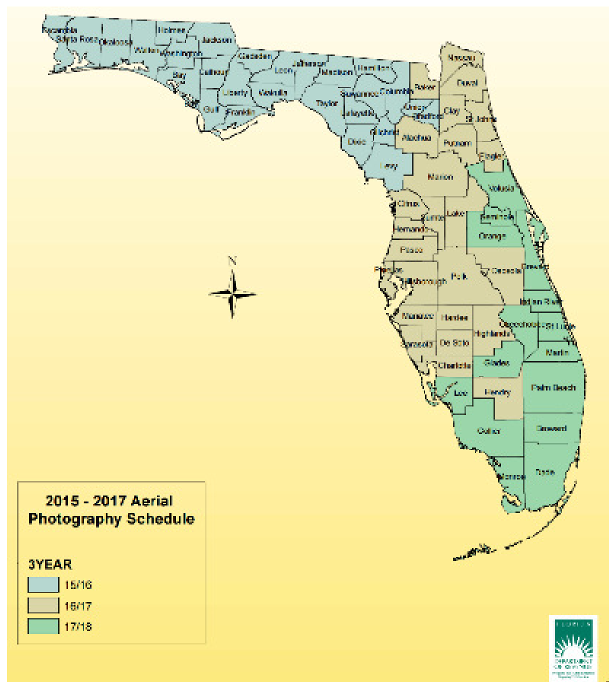


Figure 1. Florida's 3-year schedule for acquisition of digital orthophotography

- **Adhere to USGS 3DEP (https://nationalmap.gov/3DEP) data specifications and criteria**. USGS 3D Elevation Program (3DEP) is being developed to respond to growing needs for high-quality topographic data. The primary goal of 3DEP is to systematically collect enhanced elevation data in the form of high-quality LiDAR data over the country. This program published a LiDAR Base Specification (https://pubs.usgs.gov/tm/11b4) to ensure data consistency and quality, and state data acquisitions should adhere to this specification. The 3DEP is based on topographic LiDAR of three different Quality Levels:

    - QL2 is the minimum QL allowed by the 3DEP, with vertical Root Mean Square Error (RMSEz) of 10-cm (1-foot contour accuracy) and 2 or more points/m^2.
    - QL1 is a common buy-up option with RMSEz of 10-cm and 8 or more points/m^2.
    - QL0 is a less-common buy-up option with RMSEz of 5-cm (6" contour accuracy) and 8 or more points/m^2.

  All Quality Levels have comparable criteria for Non-vegetated Vertical Accuracy (NVA) in open terrain, based on RMSEz computations, and Vegetated Vertical Accuracy (VVA) in vegetated terrain based on 95th percentile computations.

Note that for the approximately 92% of the state which has LiDAR data, only 10% of that meets USGS minimum Quality Level 2 specifications, with the remaining data classified as Quality Level 3.

FEMA has now standardized on Quality Level 2 for flood risk analysis. Additionally, these same specifications stipulate temporal requirements, requiring data to have been collected within the past 8 years. Over 80% of the data collected in the state does meet this temporal requirement.

- **State funding should be used as a catalyst to stimulate joint partnerships between local government, regional government, and the private sector to pursue federal matching funds through USGS 3DEP.** Over the past 3 years, USGS 3DEP has awarded over $23M to Florida state and local governments in matching Federal funds in support of new LiDAR collection. Table 1 summarizes USGS 3DEP LiDAR investments in Florida (2015 – 2017 to date).

Table 1. Recent USGS 3DEP LiDAR Investments in Florida

Project Name	Federal Contribution	State/Tribal Contribution	Total Project Value	Square Miles	Percent of State
Northwest Florida Water Management District	$300,640	$375,200	$675,840	3,000	4.6
St. Johns River Water Management District	$87,600	$262,780	$350,380	690	1.0
Suwannee River Water Management District	$149,750	$765,170	$914,920	3,180	4.8
Palm Beach County	$177,840	$531,900	$709,740	1,995	3.0
Osceola County	$136,330	$377,840	$514,170	1,535	2.3
Martin County	$81,930	$85,000	$166,930	545	0.8
Seminole Tribe of Florida, Brighton and Big Cedar Reservations	$0	$206,250	$206,250	285	0.4
Everglades National Park	$770,590	$0	$770,590	1,211	1.8
TOTALS	**$1,704,680**	**$2,604,140**	**$4,308,820**	**12,441**	**18.9**

- **Existing data gaps should be prioritized**. As previously discussed, for over 8% of the state, no LiDAR data has been acquired. These data gaps are interior to the state and cover large conservation lands, including national preserves and forests. Due to the sparse population of these areas, it may be tempting to prioritize higher populated areas. However – as approximately 92% of the state has existing data available, these areas continue to be overlooked, and the data gaps persist. State funding should be used to ensure that these data gaps are prioritized and a baseline, high-resolution digital elevation dataset established for these areas that may continue to be of low priority to other collection efforts.

- **Florida Department of Environmental Protection Statewide LiDAR Assessment to be completed by June 2017 should be used to inform final plan for statewide acquisition.** Based on this questionnaire, Florida's LiDAR assessment is underway and will identify major business uses, LiDAR requirements, benefits and priorities. This assessment is to be completed by June 2017 and will be used to develop and implement the final plan for acquisition.

It is important for respondents to the questionnaire to understand the answers to the 12 FAQs explained, with graphic examples, below. The terms explained herein must be understood in order to provide valid responses to questions pertaining to Florida LiDAR data requirements and benefits. The individual FAQs will be repeated as you come to the relevant questions in the questionnaire.

FAQ #1: What is the difference between a LiDAR user and a LiDAR stakeholder, and who should complete the questionnaire?

A LiDAR stakeholder is a person entrusted with the success of a business or enterprise and who makes management decisions that impact business success or failure. A LiDAR stakeholder is more likely to understand costs, benefits and returns on investments (ROIs) from LiDAR.

A LiDAR user is typically a GIS technician or analyst who solves technical problems using LiDAR but who does not necessarily worry about or understand costs, benefits, and ROI.

Whereas LiDAR users can answer questions herein about their technical requirements for LiDAR data, any responses pertaining to costs or financial benefits must be reviewed and validated by a manager with some level of financial management responsibility, i.e., a stakeholder.

Either a LiDAR user or stakeholder may complete the questionnaire so long as technical requirements for topographic LiDAR, bathymetric LiDAR or topobathymetric LiDAR are established, including Quality Level, update frequency and Areas of Interest (AOIs), and so long as dollar benefits are validated by a stakeholder. If you feel that there are people in your agency, institution or company who are better qualified to answer the questionnaire or who could address a different Mission Critical Activity (MCA) requiring LiDAR, please send their name, phone number and email address as soon as possible to Jonathan Arthur (jonathan.arthur@dep.state.fl.us), Florida State Geologist. Our goal is to identify as many LiDAR MCAs as possible in Florida while avoiding duplication of effort in having multiple personnel address the same MCAs or programs.

FAQ #2: What is a Program, a Business Use (BU) and a Mission Critical Activity (MCA)?

A program is a major component of an organization that has a well-defined mission and goals and which is supported by one or more Mission Critical Activities (MCAs). For the purpose of this study, an MCA is an activity or process that uses some form of LiDAR data, including derivative products, to accomplish a Business Use (BU) for which we specify 30 pre-selected BU's for use in this LiDAR assessment. For example, within an emergency management program, hydrologic and hydraulic (H&H) modeling could be an MCA that supports BU #15 (Flood Risk Management) that requires LiDAR data for effective H&H

modeling. *Mission Critical* is defined as "indispensable for mission accomplishment and/or essential for effective/efficient operations in accomplishing the core mission of the organization."

Table 2 shows Florida's list of 30 BU's used in the questionnaire, along with examples of MCA's that fit within each BU. Questionnaire respondents will be asked to name their own MCA(s) using their own words and to also identify one of the pre-selected BU's as primary that best fits your MCA. You may also select a secondary BU, if any, that also fits your MCA.

Table 2. Business Uses and Examples of Mission Critical Activities.

Business Uses	Examples of Mission Critical Activities
BU 1 - Natural Resources Conservation	Conservation engineering. Soils and wetlands mapping and characterization. Modeling of biological and ecological systems. Erosion control. Rainfall penetration studies, impervious surfaces.
BU 02 - Water Supply and Quality	Fate and transport of contaminants. Pollution risk mitigation. Runoff and sedimentation analyses. Point- or non-point source pollution modeling. Management of contaminants and marine debris - point, non-point, vessel, and atmospheric pollution; spills; trash.
BU 03 – River and Coastal Ecosystem Management	Stream channel analysis and mapping. Stream bank erosion analysis. Aquatic and terrestrial species habitat management. Environmental management.
BU 04 - Coastal Zone Management	Analysis of coastal erosion and inundation. Hurricane storm surge and wind damage modeling and assessment. Coastal hazard modeling and mapping. Coastal hazard mitigation. Tsunami modeling. Land use and environmental planning. Oil spill modeling. Coastal resiliency. Littoral zone including dunes and beaches
BU 05 – Forest Resources Management	Forest health assessment. Determination of standing inventory of forest resources. Prescribed burn planning. Harvest systems planning.
BU 06 – Rangeland Management	Assessment of rangeland health. Mapping for soil erosion potential due to grazing.
BU 07 – Wildlife and Habitat Management	Conservation planning for wildlife refuges and marine sanctuaries. Conservation of critical habitats. Management of diverse migratory bird habitats, coral reef and coral communities, marine mammals, protected fish species, and trust resources.
BU 08 – Agriculture and Precision Farming	Farm pond design. Irrigation system design. Detailed site analysis to support precision farming. Analysis of farm sedimentation and runoff. Calibration of fertilizer application, fertilizer management and irrigation planning. Optimized terraforming.
BU 09 – Aquaculture and Fish Farming	Management of fisheries. Sustainable aquaculture. Estuary mapping and resilience.
BU 10 – Geologic Resource Assessment and Hazard Mitigation	Geologic mapping and analysis. Sinkhole and steephead mapping monitoring and analysis. Identification of geomorphologic units. Landslide hazard mapping and assessment. Karst mapping, including springs and caves. Aquifer recharge.

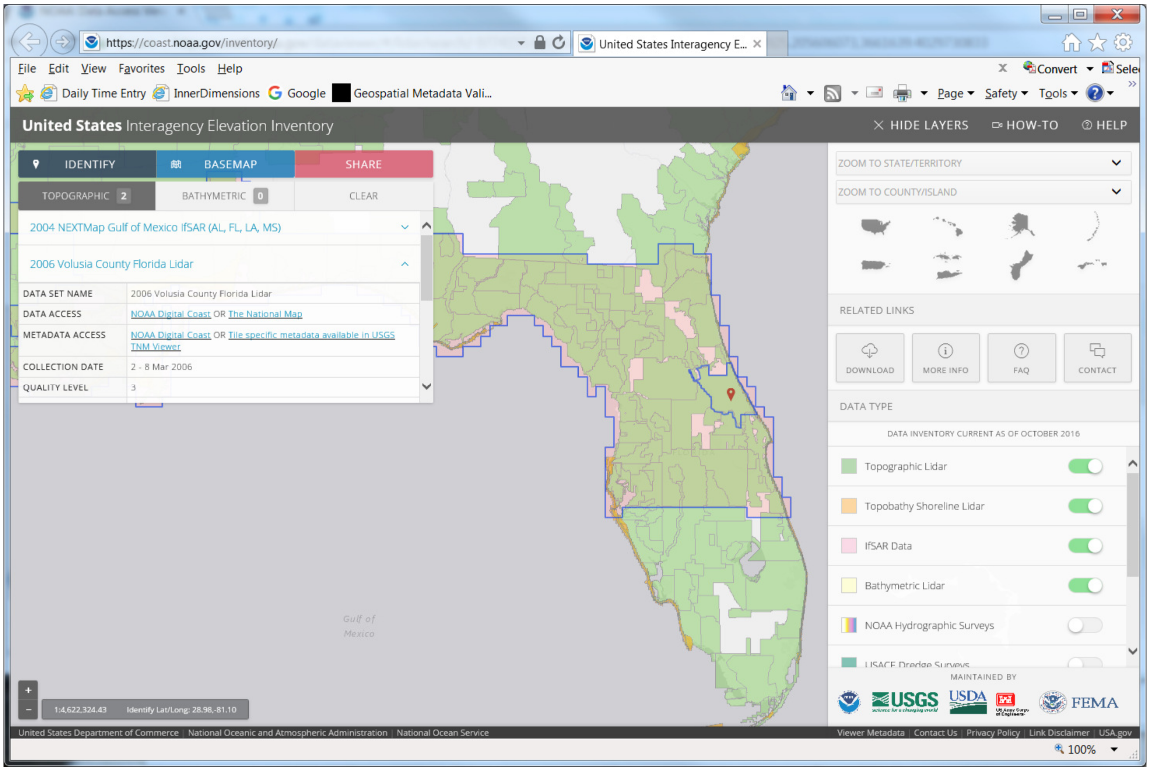
Business Uses	Examples of Mission Critical Activities
BU 11 – Resource Mining	Sediment management. Monitoring sand as a local resource. Offshore mineral extraction. Open mine volume computations. Stockpile analysis. Environmental impact assessment and site restoration.
BU 12 – Renewable Energy Resources	Alternate energy development – solar, tidal, wind, wave, and ocean current. Assessment of rooftops for solar energy potential. Analysis of wind energy potential and turbine placement. Low head power potential for hydropower.
BU 13 – Oil and Gas Resources	Oil and gas exploration and production. Pipeline and route selection. Facility siting to mitigate geologic hazards. Construction planning. Environmental impact assessment and mitigation. Regulatory compliance.
BU 14 - Cultural Resources Preservation and Management	Discovery and analysis of underwater archaeological and historical cultural sites. Site protection and preservation planning. Discovery and analysis of Native American and other historical cultural sites and subsistence activities.
BU 15 – Flood Risk Management	Flood risk modeling and mapping of riverine and coastal areas. Dam/dike/levee safety analysis. Emergency management. Flood forecasts.
BU 16 – Sea Level Rise and Subsidence	Modeling and mapping the effects of sea level rise or subsidence. Population and economic vulnerability assessments. Coastal inundation and infrastructure assessment.
BU 17 – Wildfire Management, Planning, and Response	Determination of forest fuel and fire susceptibility. Fire behavior modeling to support wildfire suppression activities. Wildland/urban interface building identification. Post fire analysis to determine landslide prone areas.
BU 18 – Homeland Security, Law Enforcement, and Disaster Response Emergency Management	Infrastructure and border protection. Coastal search and rescue. Population dynamics. Emergency fuel supply and movement. Line of sight analysis in urban areas. Flood risk analysis resulting from acts of terrorism.
BU 19 – Land Navigation and Safety	Road/railroad route selection and maintenance. Slope analysis for autonomous cars. GPS navigation visualization.
BU 20 – Marine and Riverine Navigation and Safety	Nautical charting. Bathymetric measurements of near-shore submerged coastal topography. Identification of hazards to navigation in ports, rivers, navigable waterways. Sediment management at coastal navigation projects. Precision marine navigation.
BU 21 – Aviation Navigation and Safety	Determination of in-flight hazards and path obstructions. Aeronautical charting. Runway construction and repair.
BU 22 – Infrastructure and Construction Management	Marine construction. Bridge design and construction. Engineering and construction of dams, levees, dikes, reservoirs, and coastal structures. Shipyard and port construction. Water, sewer, or power line planning and vegetation analysis. Pump, drain and well placement. Stormwater modeling. Cut and fill analysis for earth-moving. Building site analysis. Road infrastructure.
BU 23 – Urban and Regional Planning	Land development and zoning. Municipal mapping of building footprints and elevations. Stormwater management. Port resilience planning. Parks and transportation planning. Virtual city creation. Urban ecology planning.

Business Uses	Examples of Mission Critical Activities
BU 24 – Health and Human Services	Health emergency response. Habitat modeling and disease prevention. Defining boundaries for health advisories for swimming and fishing. Marine-based bio products and pharmaceuticals. Public health and safety. Prevention of waterborne diseases.
BU 25 – Real Estate, Banking, Mortgage, and Insurance	Assessment of risk for natural hazards (e.g., sinkholes, flooding) to inform insurance policy rates and the determination of mandatory insurance. Building permit compliance.
BU 26 – Education K-12 and Beyond; Basic Research	Development of 3-D visualizations to help students understand the Earth they live on. Understanding of continental-scale climate change impacts. Ocean science. Ocean education. Scientific research. Data dissemination. Development of training simulators.
BU 27 – Recreation	Planning and development of recreational facilities such as rafting, boating, swimming, diving, and fishing areas, springs and golf courses. Location-based products and services such as maps and guides. Tourism. Trail and vista site planning. Orienteering.
BU 28 - Telecommunications	Telecommunication tower site selection. Design of radio and radar systems. Interference analysis. Path profiles. Undersea telecommunication route selection and deployment.
BU 29 - Military	Tactical military operations. Strategic defense. Amphibious landings and logistics over-the-shore. Operation of ships and submarines. Weapons system testing. Management of flight facilities and offshore launch or target areas.
BU 30 – Maritime and Land Boundary Management	Delimitation of legal and other coastal boundaries, inland boundaries, ordinary high water lines (OHWL).

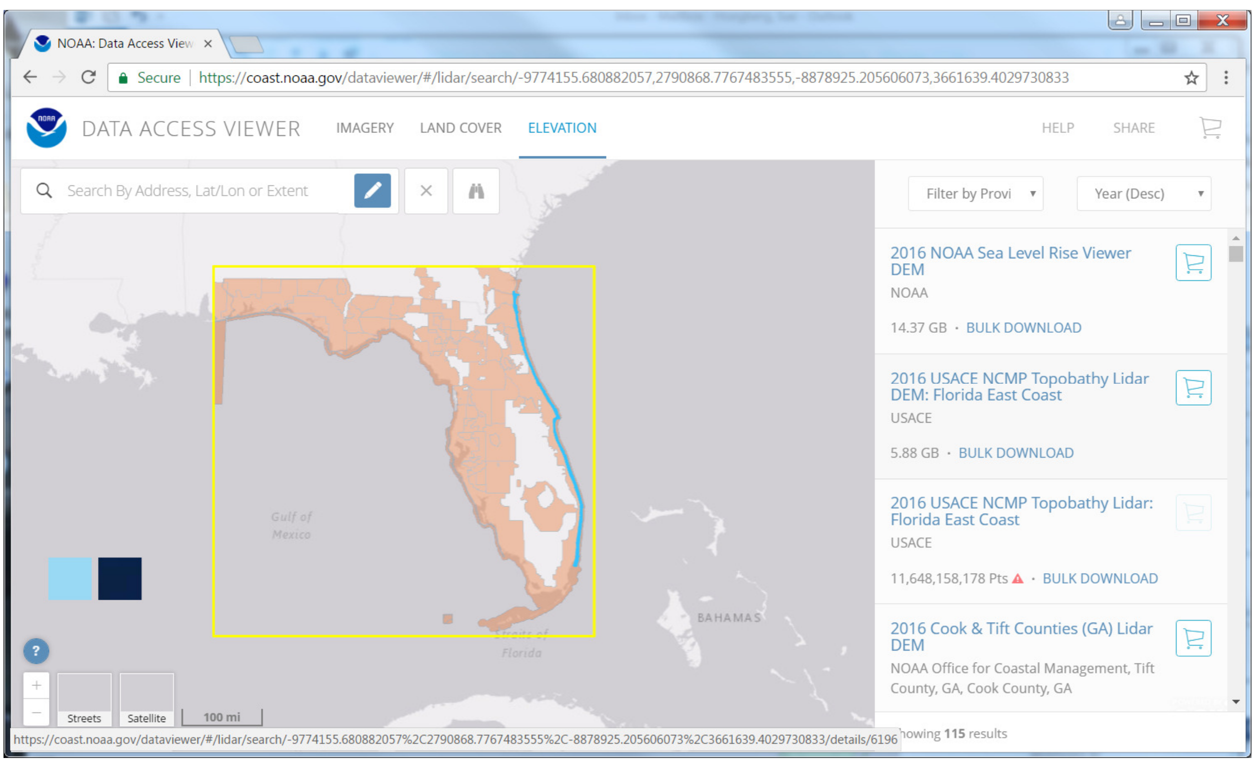
FAQ #3: How do I find out what topographic or bathymetric data are currently available in Florida?

LiDAR users and stakeholders need to know what LiDAR data already exists in Florida in order to better understand future requirements for more current and accurate LiDAR datasets. There are two Federal on-line inventories of elevation data where you can see what data are available, when they were collected, by whom, and to what level of accuracy. Each includes data collected by Federal, state, and local agencies, but may not include all locally or privately collected elevation datasets.

The U.S. Interagency Elevation Inventory is available here: https://coast.noaa.gov/inventory/. It includes information about offshore bathymetry as well as topographic and topobathymetric data. You can turn on and off the different data types and view their date and Quality Level. You can also download the spatial data for the inventory for further review or analysis.

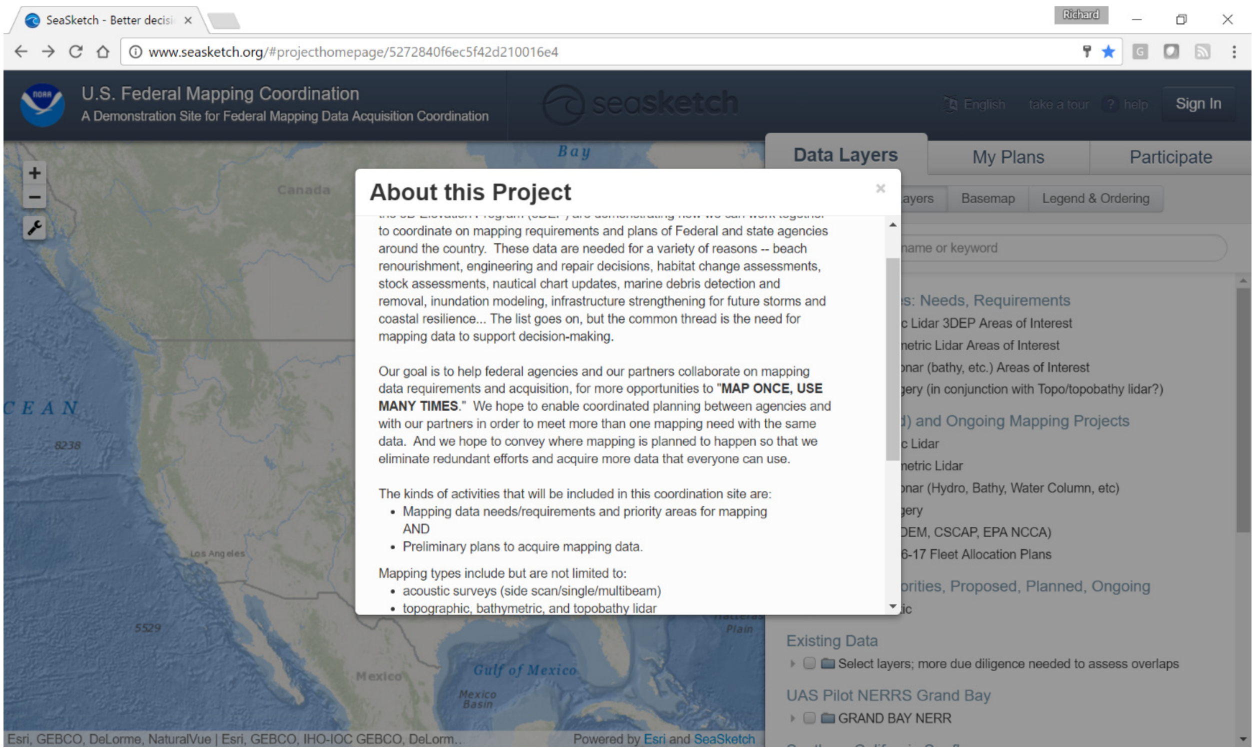


NOAA's Data Access Viewer is available here: https://coast.noaa.gov/dataviewer/#/lidar/search/. This is for LiDAR data download. You can also download actual elevation data from this site.

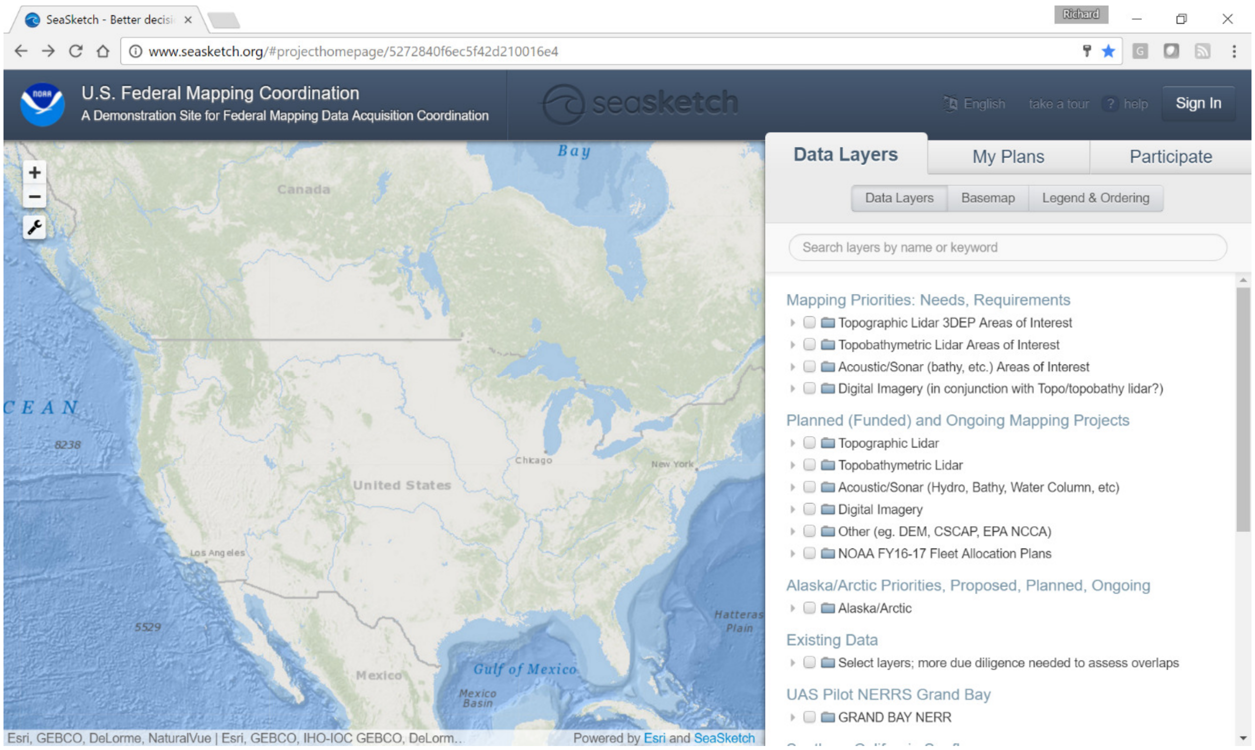


FAQ #4: How do I enter unique geographic area requirements for the 2017 Florida DEP Statewide LiDAR Assessment that are not covered by standard pick lists in the questionnaire?

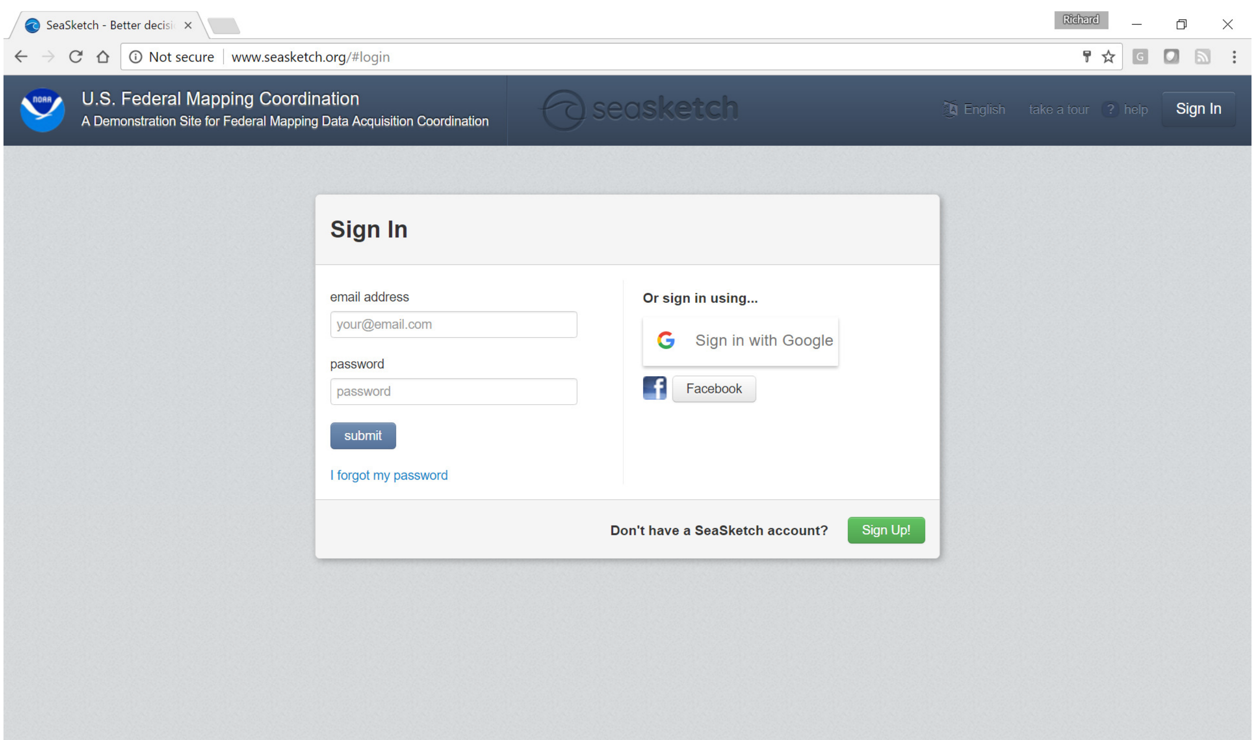
- Visit SeaSketch **U.S. Federal Mapping Coordination Site** available at http://www.seasketch.org/#projecthomepage/5272840f6ec5f42d210016e4.



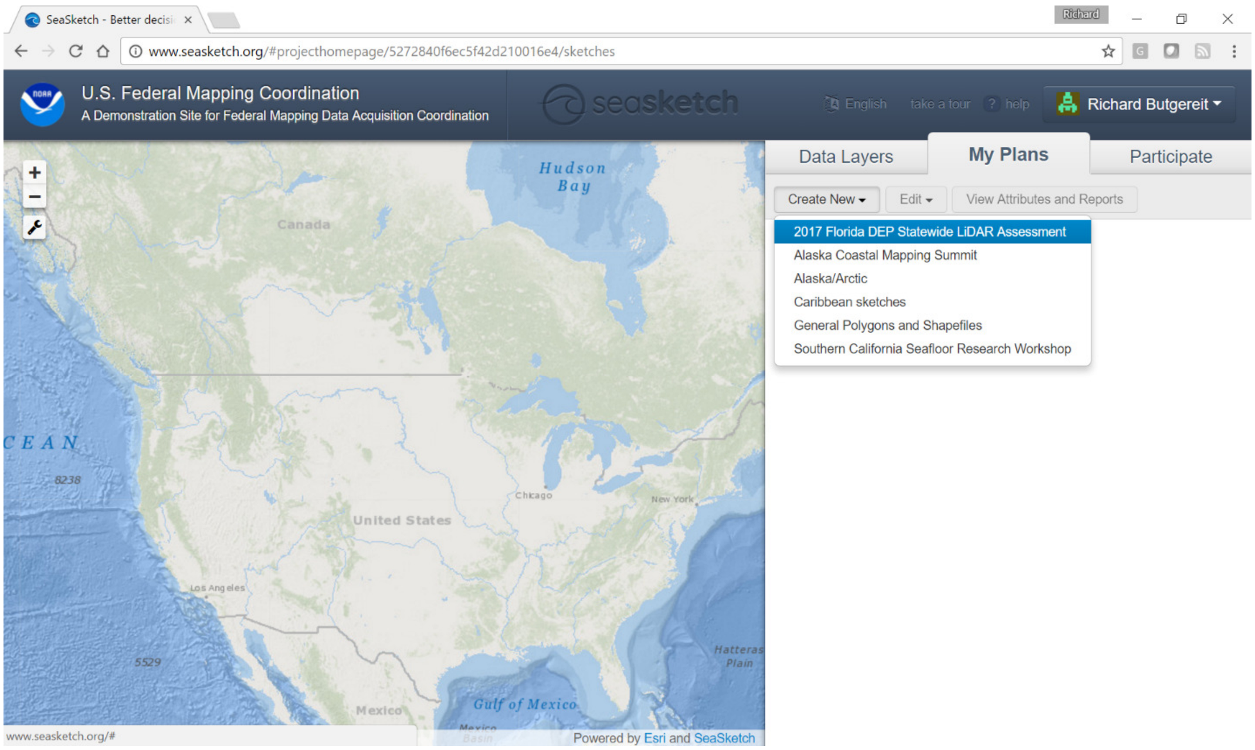
- Click **X** in the upper, right-hand side of the pop-up window to dismiss **About this Project**
- Click **Sign In** in the upper, right-hand side of the **U.S. Federal Mapping Coordination** window



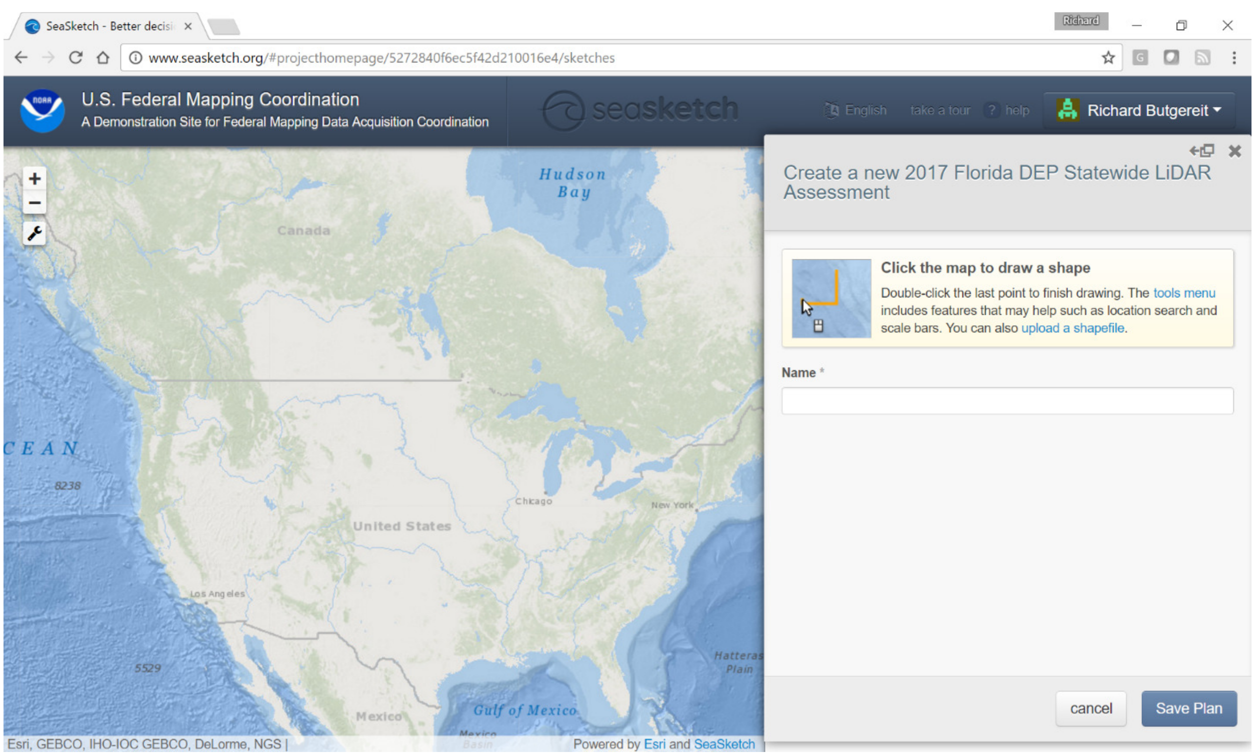
- Enter credentials to sign in or click **Don't have a SeaSketch account** to create an account



- Click **My Plans**, select **Create New**, pull down and select **2017 Florida DEP Statewide LIDAR Assessment**



- Provide a Name and follow the steps to either digitize or upload a shapefile of your project area.



FAQ #5: What is the difference between topographic LiDAR and bathymetric or topobathymetric LiDAR, and what are their advantages and limitations?

Airborne Light Detection and Ranging (LiDAR) is a remote sensing technique used to measure the distance to an object by determining the time of flight for an emitted laser beam. A scanning mechanism (such as an oscillating mirror) is typically employed to steer a series of laser pulses (typically over 100 KHz) over a wide area from an airborne platform. All airborne LiDAR systems use enabling technologies such as Global Positioning System (GPS) and Inertial Measurement Unit (IMU) to determine the location and orientation of the remote sensor located on the airborne platform.

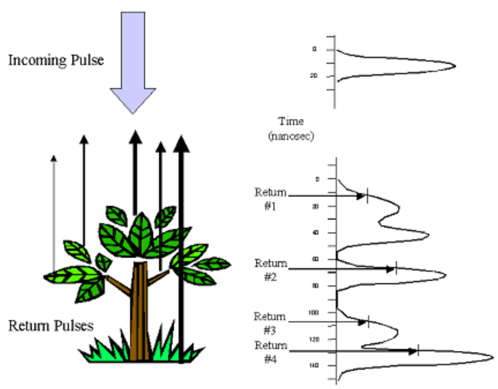


Figure 2. Topographic LiDAR, with near infrared laser, maps ground topographic features, vegetation and manmade features; unreliable for water surface and below

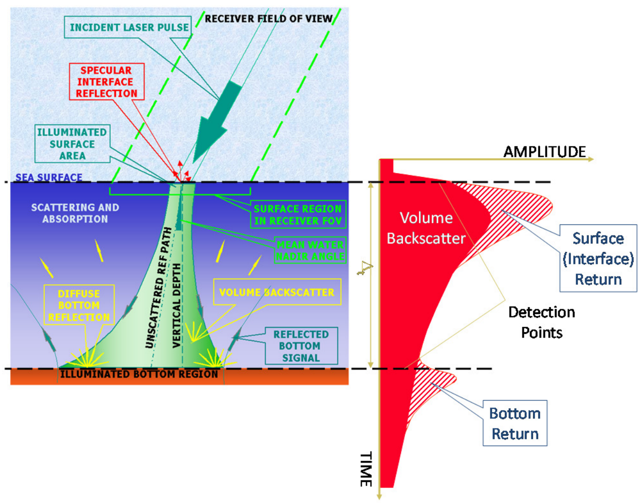


Figure 3. Bathymetric and topobathymetric LiDAR, with green laser, maps water surface and submerged topography. Graphic credit: JALBTCX.

Topographic LiDAR systems typically use a near infrared laser pulse to measure topography of the land surface, features and objects on land, such as building structures and vegetation, as well as bare earth topography under vegetation (Figure 2).

Airborne LiDAR Bathymetry (ALB) is a technique for measuring the depths of moderately clear, near-shore coastal waters, lakes, and rivers from a low-altitude aircraft using a green-wavelength scanning, pulsed laser beam. ALB have larger beam divergence and have greater depth penetration capability, up to 60 m water depths in clear water, and use sophisticated waveform analysis-based algorithms to determine water depth (Figure 3). *Topobathymetric LiDAR systems*, also called topobathy systems, have smaller beam divergence with less penetration capability, up to 10 m water depths in clear water, and rely on a simple refraction correction technique to determine water depth. Most bathymetric and topobathymetric LiDAR systems can also provide topography data over land areas.

LiDAR Advantages

Topographic LiDAR routinely penetrate foliage where photogrammetry, which relies on aerial photography, cannot see the ground in stereo to map the bare-earth ground beneath.

LiDAR uses up to 500,000 laser pulses per second to map 3-D coordinates from first, last, and intermediate returns from each laser pulse. The first return can be used to map the top reflective surface (DSM). Intermediate returns provide additional information about vegetation. The last return is used to map the bare-earth terrain (DTM); however, because last returns include elevations on rooftops and vegetation too dense to be penetrated, LiDAR last returns still require automated filtering and some manual filtering of LiDAR "point clouds" to produce the bare-earth surface. Figure 4 shows how it takes only a single LiDAR pulse to penetrate vegetation. Figures 5 and 6 show how LiDAR penetrates dense vegetation in Florida that normally could not be mapped by other technologies such as photogrammetric stereo compilation.

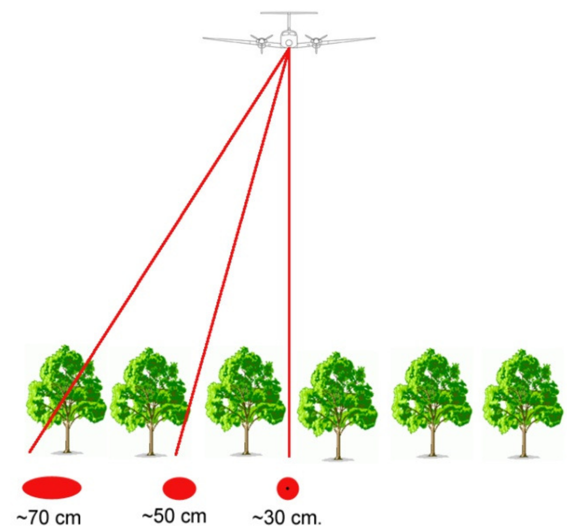


Figure 4. LiDAR can map the bare-earth terrain in forests by single pulses that penetrate *between* trees and even *through* trees in some instances. The footprint size of each laser pulse varies by the angle of the scan, as shown here. Normally acquired in zig-zag patterns, LiDAR scans are so dense that scan lines are nearly parallel. Flying higher with a high pulse rate and narrow left-right scan angle allows a high point density and increased ability to penetrate dense vegetation by having near-vertical laser pulses that can better penetrate between trees.

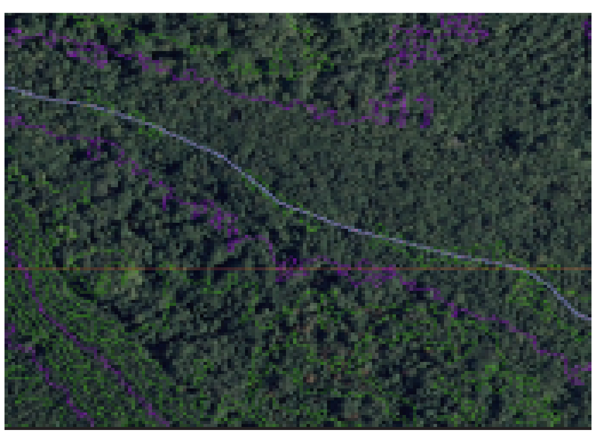


Figure 5. In spite of dense vegetation shown on this orthophoto in Florida, LiDAR data collected at a point density of 4 points/m^2 was still able to establish a hydro flow line for the dry drainage feature beneath.

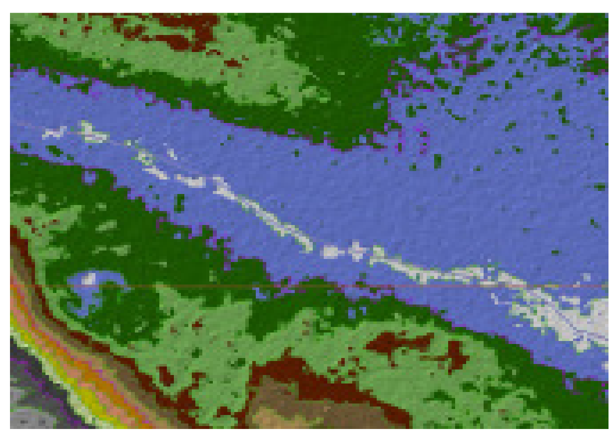


Figure 6. Color-coded by 1-foot contour elevation bands, the white polygons define depression contours that show dry *puddles* that should not normally be hydro-enforced (defined below). This does not necessarily work in mangrove and sawgrass.

<u>LiDAR Limitations</u>

The major limitation of topographic LiDAR is that it cannot penetrate to the bare earth if the vegetation is too dense that pulses of laser light cannot penetrate through gaps in the canopy to reach the ground. As a rule of thumb, on a bright sunny day, if sunlight is "seen" on the ground, then it is possible to map that ground with LiDAR. Sometimes, increasing the point density can improve the probability of the laser pulse to find a gap in the canopy to reflect off the ground. As a result, a QL1 LiDAR dataset may produce a better ground model than a QL2 LiDAR dataset, due to the increased point density. However, there are several instances when increasing the point density will not help produce a better ground model. Figure 7 shows an example of last return topographic LiDAR for which Dewberry performed a field check to determine what kind of vegetation was on the left side of this image and what was on the right side. We found that the artifacts on the left side resulted from a corn field that was so dense that the LiDAR pulses could not penetrate to the ground. Dewberry found examples similar to this with sugar cane fields in Hawaii and mangrove and sawgrass in Florida. In such cases, it is normal for the LiDAR analyst to classify these points as non-ground and then interpolate the DEM from surrounding points that are considered to be ground. This works acceptably in many cases, and especially when the surrounding ground area is flat, as is normally the case in Florida. We found that the apparent artifacts on the right side of Figure 7 were not artifacts at all but actually the bare earth terrain in a forested area as shown in Figure 8. In forested areas, it is typical for the bare earth terrain to be irregular or undulating.

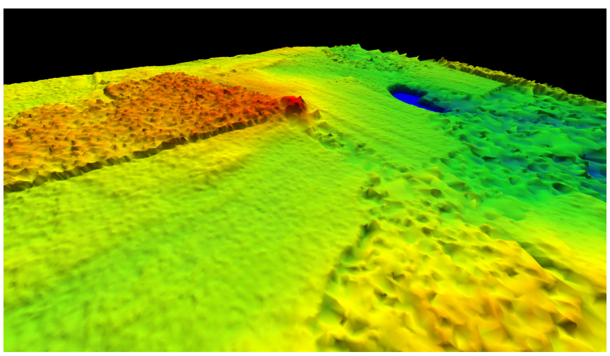


Figure 7. The artifact on the left is a dense corn field where the LiDAR failed to penetrate to the ground. The irregular areas on the right are legitimate, as shown in Figure 8, and should not be smoothed.

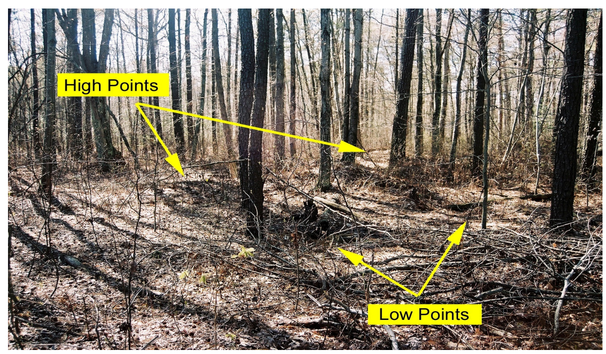


Figure 8. This image correlates with the irregular terrain shown on the right of Figure 7. In such areas, it is acceptable and expected that the bare earth DEM will not be smooth.

A second limitation of topographic LiDAR is that there are sometimes void areas in urban canyons and areas with tall buildings that block non-vertical LiDAR pulses from reaching the ground. These void areas are immediately adjacent to tall buildings. This problem is minimized by flying higher with higher point density and/or by flying east-west flight lines in addition to north-south flight lines, for example.

The major limitation of bathymetric or topobathymetric LiDAR is that success is largely dependent on the clarity of the water. Bathymetric or topobathymetric LiDAR cannot map the subsurface terrain beneath the muddy Mississippi River, lakes covered with algae, wetlands with murky waters, and shorelines with high sediment suspension from surf action. See Figures 9 and 10. The ability to determine the sea bottom is also dependent on the type of sensor being used. Traditional bathymetric Lidar sensors that have a high-power wide beam are able to better penetrate through turbid waters.

Topobathymetric sensors typically have lower power and utilize a narrow beam that results in more potential voids in turbid waters, but they are cheaper to operate. Bathymetric surveys must be conducted during periods of most optimal water clarity; sometimes water clarity changes seasonally or even daily.

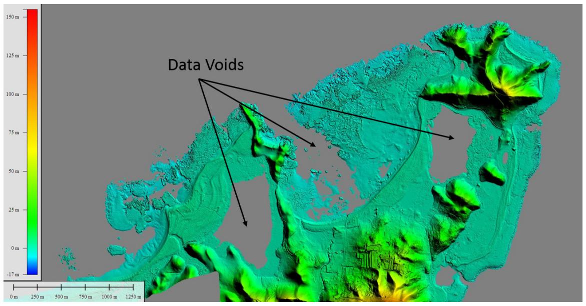


Figure 9. Topobathymetric LiDAR data voids caused by bio-luminescence in this bay in Puerto Rico

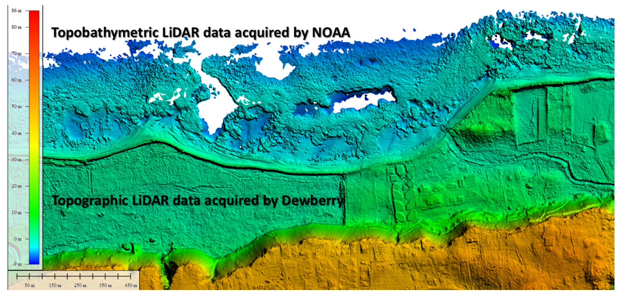


Figure 10. Topobathymetric LiDAR data voids caused by surf with suspended sediments

Depending on the technology used and time of survey, topobathymetric LiDAR may be expected to work in several of Florida's clear springs, some wetland environments, and in shallow Florida bays when waters are clear, but it is not expected to perform very well in Florida's larger rivers, intracoastal waterways and lakes that are turbid. A mix of topobathymetric LiDAR and acoustic (multibeam sonar) surveys would be required for most bathymetric areas in Florida.

FAQ #6: Are you familiar with the 3D Elevation Program (3DEP) and 3D Nation and DEM terminology for defining topographic and bathymetric LiDAR Quality Levels (QLs)?

The USGS 3DEP is the elevation layer of The National Map, replacing the former National Elevation Dataset (NED). The 3DEP consists of QL5 IFSAR of Alaska and QL2 or better topographic LiDAR for the remaining 49 states and U.S. territories based on the USGS Base Lidar Specification V1.2 with major density and accuracy parameters as shown in Table 3. The goal of the 3DEP is to acquire QL2 or better LiDAR data nationwide, updated on an 8-year cycle, with cost sharing between numerous stakeholders.

Table 3. Topographic LiDAR Density and Absolute Vertical Accuracy

Quality Level (QL)	Aggregate Nominal Pulse Spacing (ANPS)	Aggregate Nominal Pulse Density (ANPD)	$RMSE_z$ (non-vegetated)	NVA at 95% confidence level	VVA at 95th percentile	Equivalent Contour Accuracy
QL0	≤0.35 m	≥8 pts/m^2	≤5 cm	≤9.8 cm	≤14.7 cm	~ 6 inch
QL1	≤0.35 m	≥8 pts/m^2	≤10 cm	≤19.6 cm	≤29.4 cm	~ 1 foot
QL2	≤0.71 m	≥2 pts/m^2	≤10 cm	≤19.6 cm	≤29.4 cm	~ 1 foot

Caution!

The nationwide 3DEP program is based on QL2 LiDAR or better. Please note that QL0 LiDAR is more expensive than QL1 LiDAR which is similarly more expensive than QL2 LiDAR. LiDAR users should not over-specify their accuracy requirements just because highest accuracy would be nice-to-have.

The 3D Nation is a concept for acquiring consistent and seamless high-accuracy, high-resolution elevation data from the tops of the mountains to the depths of the seas, primarily through a combination of topographic LiDAR (from the 3DEP to specifications in Table 3), as well as bathymetric LiDAR and sonar (to specifications in Table 4). The National Science and Technology Council has developed the National Coastal Mapping Strategy 1.0: *Coastal LiDAR Elevation for a 3D Nation*, in which it proposes bathymetric equivalents ($QL0_B$, $QL1_B$, $QL2_B$, $QL3_B$ and $QL4_B$) to topographic LiDAR Quality Levels in the USGS Lidar Base Specification (QL0, QL1, and QL2) as summarized in Table 3.

User requirements for bathymetric and/or topobathymetric LiDAR will be defined at five potential bathymetric Quality Levels (Table 4) consistent with standards of the International Hydrographic Office (IHO), USACE hydrographic survey requirements, the IWG-OCM National Coastal Mapping Strategy and Quality Levels being considered for the 3D Nation Requirements and Benefits Study by USGS and NOAA. Note that $QL0_B$ and $QL1_B$ are equivalent to the IHO Special Order standard for vertical accuracy, and the vertical accuracy specification for $QL4_B$ is equivalent to the IHO Order 1 standard for vertical accuracy. The higher-density $QL0_B$ and $QL2_B$ are better for detection of submerged objects that may be hazardous to marine navigation.

Table 4. Bathymetric/Topobathymetric LiDAR Density and Absolute Vertical Accuracy

	$QL0_B$	$QL1_B$	$QL2_B$	$QL3_B$	$QL4_B$
Aggregate Nominal Pulse Spacing	≤0.7m	≤2.0 m	≤0.7 m	≤2.0 m	≤5.0 m
Aggregate Nominal Pulse Density	≥2.0 pts/m^2	≥0.25 pts/m^2	≥2.0 pts/m^2	≥0.25 pts/m^2	≥0.04 pts/m^2
Depth Examples (m)	**Vertical Accuracy of submerged elevations at 95% Confidence Level (cm)**				
0	25.0	25.0	30.0	30.0	50.0
10	26.1	26.1	32.7	32.7	51.7
20	29.2	29.2	39.7	39.7	56.4
Applications	Detailed site surveys requiring the highest accuracy and highest resolution seafloor definition; dredging and inshore engineering surveys; high-resolution surveys of ports and harbors		Charting surveys; regional sediment management; general bathymetric mapping; coastal science and management applications; change analysis; deep water surveys; environmental analyses		Recon/planning; all general applications not requiring higher resolution and accuracy

Digital Elevation Model (DEM) Terminology —

Digital Elevation Model (DEM) — An elevation model of the bare earth terrain interpolated from irregularly-spaced mass points so as to produce a uniformly-gridded surface with more-efficient file storage. When looking closely at how DEMs are stored, they are seen to be extremely efficient.

DEMs can be viewed as pixels, color-coded by elevation, as shown at Figure 11. DEMs have small file sizes because incrementing x/y by Δx and Δy eliminates the need for storing individual x/y coordinates, as shown at Figure 12.

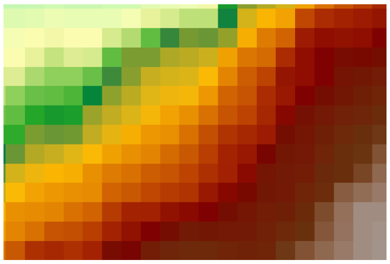


Figure 11. DEM viewed as pixels, color-coded by elevation

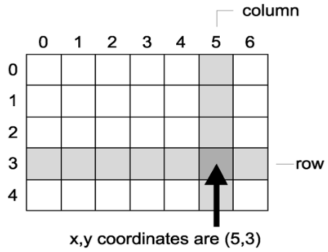


Figure 12. DEM files are small and efficient because individual x/y coordinates do not need to be stored

Digital Elevation Model (DEM) Resolution — The linear size of each cell of a uniformly-gridded raster DEM. DEM cell sizes are normally expressed in whole metric units, e.g., 1m cell size. DEM resolution may be referred to as cell size, grid spacing, or ground sample distance which is defined as the standard 3DEP product. It is common to depict a DEM cell as having a single elevation post per grid cell, as shown in Figure 13.

Mass Points — Irregularly-spaced points, each with x/y location coordinates and z-value, typically (but not always) used to form a Triangulated Irregular Network (TIN) from which uniformly-gridded DEMs are interpolated. When generated automatically, e.g., by LiDAR scanners, mass point spacing and pattern depend upon the characteristics of the technologies used to acquire the data.

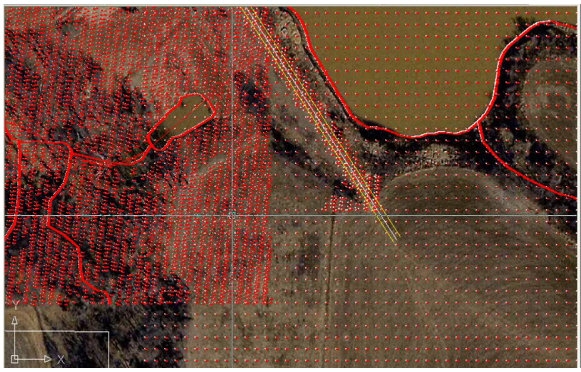


Figure 13. Higher density, irregularly-spaced LiDAR mass points (red) are used to interpolate the lower density DEM elevation posts shown on the right. Several hydro breaklines are also shown in this image.

Breakline — A linear feature that describes a change in the smoothness or continuity of a surface. The two most common forms of breaklines are as follows:

- A ***soft breakline*** ensures that known z-values along a linear feature are maintained (e.g., elevations along a pipeline, road centerline or drainage ditch), and ensures that linear features and polygon edges are maintained in a TIN surface model, by enforcing the breaklines as TIN edges. They are generally synonymous with 3D breaklines because they are depicted with series of x/y/z coordinates. Somewhat rounded ridges or the trough of a drain may be collected using soft breaklines.

- A ***hard breakline*** defines interruptions in surface smoothness, e.g., to define streams, rivers, shorelines, dams, ridges, building footprints, and other locations with abrupt surface changes. Although some hard breaklines are 3D breaklines, they are typically depicted as 2D breaklines because features such as shorelines and building footprints are normally depicted with series of x/y coordinates only, often digitized from digital orthophotos that include no elevation data.

Root Mean Square Error (RMSE) — The square root of the average of the set of squared differences between dataset coordinate values and coordinate values from an independent source of higher accuracy for identical points. The RMSE is used to estimate the absolute accuracy of both horizontal and vertical coordinates when standard or accepted values are known, as with GPS-surveyed check points of higher accuracy than the data being tested. In the United States, the independent source of higher accuracy is expected to be at least three times more accurate than the dataset being tested.

RMSEz — The vertical RMSE ($RMSE_Z$) is calculated as the square root of $\sum(Z_n - Z'_n)^2/N$, where:

- Z_n is the set of N z-values (elevations) being evaluated, normally interpolated (for TINs and DEMs) from dataset elevations of points surrounding the x/y coordinates of checkpoints
- Z'_n is the corresponding set of checkpoint elevations for the points being evaluated
- N is the number of checkpoints
- n is the identification number of each of the checkpoints from 1 through N.

Equivalent Contour Accuracy — The equivalent contour accuracy is 3 times the RMSEz. For example, RMSEz of 10 cm is equivalent to 30 cm contours, and RMSEz of 0.333' (4") is equivalent to 1 foot contours.

Non-Vegetated Vertical Accuracy (NVA) — The value by which vertical accuracy of topographic LiDAR in non-vegetated areas can be equitably assessed and compared among datasets when applying the ASPRS Positional Accuracy Standard for Digital Geospatial Data. The NVA is determined with well-distributed checkpoints located in both open terrain (bare soil, rock, sand and short grass) and urban terrain (concrete and asphalt surfaces). The NVA is determined by multiplying RMSEz x 1.9600.

Vegetated Vertical Accuracy (VVA) — The value by which vertical accuracy of topographic LiDAR in all vegetated areas can be equitably assessed and compared among datasets when applying the ASPRS Positional Accuracy Standards for Digital Geospatial Data. The VVA is determined with well-distributed checkpoints located in all vegetated land cover categories combined, including tall weeds and crops, scrub forests, and fully forested areas, as well as other localized vegetation categories such as mangrove or sawgrass (unless specifically identified as Low Confidence Areas, defined below). The VVA is determined by using the 95^{th} percentile (rather than using an RMSEz multiplier, because errors in vegetation do not necessarily follow a normal error distribution.

Bathymetric Vertical Accuracy — The value by which vertical accuracy of submerged topography mapped with topobathymetric or bathymetric LiDAR can be equitably assessed and compared among datasets when applying the ASPRS Positional Accuracy Standard for Digital Geospatial Data. For practical purposes, absolute vertical accuracy of submerged topography can only be determined for nearshore bathymetry where GPS antenna on elevated range poles can be used to measure submerged QA/QC checkpoints. Then, the vertical accuracy is determined by multiplying RMSEz x 1.9600.

Nominal Pulse Spacing (NPS) — A common measure of the density of a LiDAR dataset, it is the typical or average lateral distance between points in a LiDAR dataset, most often expressed in meters. NPS refers to the average point spacing of a LiDAR dataset typically acquired in a zig-zag pattern with variable point spacing along-track and cross-track. NPS is an estimate and not an exact calculation.

Aggregate Nominal Pulse Spacing (ANPS) — A variant of nominal pulse spacing (NPS) that expresses the typical or average lateral distance between pulses in a LiDAR dataset resulting from multiple passes of the LiDAR instrument, or a single pass of a platform with multiple LiDAR instruments, over the same target area.

Nominal Pulse Density (NPD) — A common measure of the density of a single pass (single swath) of LiDAR data, expressed as points per square meter (PPSM), normally used when the Nominal Pulse Spacing (NPS) is less than one meter. PPSM = $1/NPS^2$.

Aggregate Nominal Pulse Density (ANPD) — A variant of nominal pulse density (NPD) that expresses the total expected or actual density of pulses occurring in a specified unit area resulting from multiple passes of the LiDAR instrument, or a single pass of a platform with multiple LiDAR instruments, over the same target area.

With only 10% sidelap between adjacent flight lines, the left side of Figure 14 shows that the majority of the area is mapped with a single swath -- relevant to the terms NPS and NPD. With 50% sidelap, the right side of Figure 14 shows that the majority of the area is mapped with two swaths -- relevant to the terms ANPS and ANPD, increasing the probability of penetrating dense vegetation by having two different look angles. A sidelap of 50% doubles the ANPD compared with single swaths with 10% side lap.

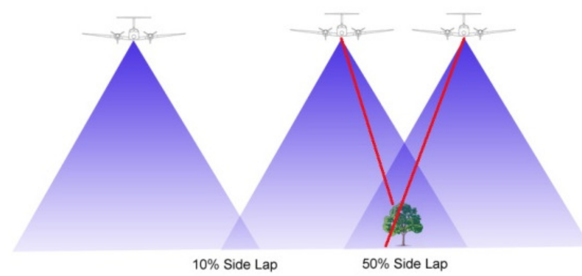


Figure 14. Comparison between 10% and 50% side lap between overlapping LiDAR swaths; 50% side lap typically doubles the aggregate nominal point density

<u>How to determine NPS or DEM post spacing requirements.</u>

The determination of the <u>minimal acceptable</u> point density, DEM post spacing and/or NPS needed to satisfy Business Uses is central to the purpose of this questionnaire. Respondents should <u>not</u> specify requirements that are "nice to have" but focus instead on minimal acceptable requirements for satisfaction of their Business Uses. Several considerations are suggested below, but ultimately this must be the decision of elevation data users that best understand their technical requirements.

Five questions should be considered:

1. What level of detail do you need to see from the elevation data?
2. What are your needs for feature extraction?
3. What do you need to measure?
4. How dense is the vegetation you need to penetrate?
5. What are your needs for breaklines?

Consideration #1 (What you need to see). For some Business Uses, users need to be able to *see* certain terrain features to be analyzed, to include overhead power lines. It is easier to see the visual effects of resolution than the visual effects of elevation accuracy. If you can *see* what you need from Florida's existing LiDAR data, the status quo may be acceptable unless the data are obsolete.

Consideration #2 (Features you need to extract). A high resolution DEM is often required if LiDAR data are to be used for automated or semi-automated feature extraction, as shown in Figures 15 and 16.

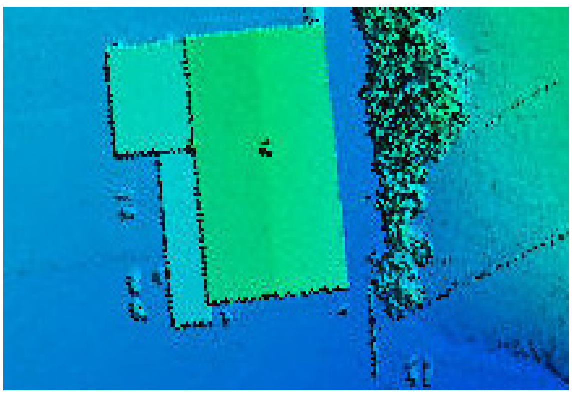


Figure 15. Even with sub-meter NPS, building footprint edges are pixilated. Straight edges are difficult to define when they are irregular and pixilated.

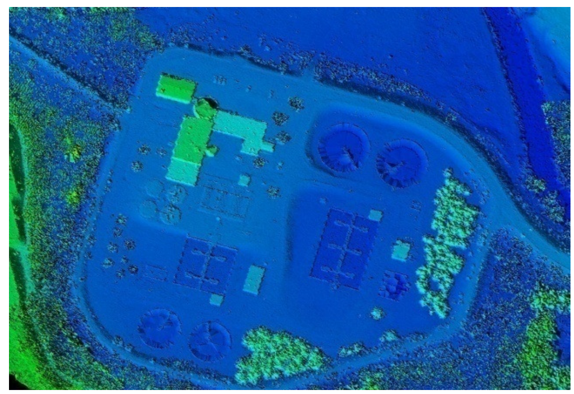


Figure 16. High resolution elevation data are required when LiDAR is used for semi-automated feature extraction. Many misclassifications result from low resolution elevation data.

Consideration #3 (What you need to measure). Your DEM user application has everything to do with required point density. Table 5, below, shows examples where measurements are made for landslides, morphology, building classification, fire loads, tree species, forest metrics, vegetation classification, and measurement of the DTM in the forest floor. Other applications might include assessment of forest health.

Consideration #4 (Density of vegetation to be penetrated). In some cases, the raw LiDAR point density per square meter or the NPS is much more important than the DEM post spacing, especially in areas of dense vegetation. Figures 5 and 6 (see FAQ #7) show an example of LiDAR data in Florida where the points were collected with an average density of 4 points/m^2 in dense tropical vegetation. This worked in Florida, but in the Pacific Northwest users had many tall, dense forests where they needed QL1 LiDAR with 8 points/m^2 for forestry and geology applications.

Table 5 addresses both considerations #3 and #4.

Table 5[1]. Watershed Sciences, Inc.'s recommended resolution for demanding LiDAR applications in the Pacific Northwest. Most other applications are satisfied by lower-resolution LiDAR datasets. (Florida has similar issues in swamps and other areas of dense vegetation defined as "low confidence areas.")

Florida Alert

Typically in Florida swamps with mangrove, sawgrass and other dense vegetation, Dewberry determined that less than 5% of LiDAR laser pulses penetrated the vegetation to the ground. Thus, an Aggregate Nominal Pulse Density of 8 pts/m^2 may yield few if any points on the ground in such areas defined as "low confidence."

Discipline	Application	Recommended Density, pulses per m^2 and (NPS)	
		Low	High

[1] From a paper entitled, "Minimum LiDAR Data Density Considerations for the Pacific Northwest," 01/22/10, by Watershed Sciences, Inc., now part of Quantum Spatial Inc.

Geology	Landslides	4 (0.50 m)	4 (0.50 m)
	Morphology	5 (0.45 m)	8 (0.35 m)
Urban Planning	Building Classification	4 (0.50 m)	8 (0.35 m)
Fire Modeling	Fire Loads	4 (0.50 m)	8 (0.35 m)
	Mapping Burns	4 (0.50 m)	6 (0.41 m)
Forestry with Pacific Northwest-specific Applications	Tree Species Identification	4 (0.50 m)	6 (0.41 m)
	Forest Measurement and Monitoring	4 (0.50 m)	4 (0.50 m)
	Tree Height Measurements	4 (0.50 m)	6 (0.41 m)
	Vegetation Characterization	4 (0.50 m)	8 (0.35 m)
	DTM Accuracy under Canopy Cover	4 (0.50 m)	6 (0.41 m)

Figure 13 demonstrated that the NPS must be denser than the DEM post spacing. This Oregon study shows that it is not just the raw LiDAR points that must be denser than the DEM, but the percent of the raw LiDAR points that penetrate the vegetation to the ground. There is no substitute for prior experience in comparable vegetation to determine what percent of the LiDAR points are expected to penetrate to the ground so that the NPS requirements can be adjusted accordingly – prior to data acquisition.

Consideration #5 (Breakline needs). Breaklines may be especially relevant in Florida to define subtle breaks in topography that could potentially affect direction of surface water flow. Most organizations establish their own requirements for breaklines.

Figure 17 shows typical LiDAR mass points with NPS of approximately 1 meter. For most automated processes, these elevation points adequately model the terrain. Figure 18 shows breaklines produced from these LiDAR mass points for which fewer model key points were retained after manual compilation of the breaklines shown. It is true that contour lines produced from the model key points and breaklines will be more aesthetically pleasing, but this rarely helps automated processes. A decision must be made if the "Chevy version" at Figure 17 is acceptable, or if the "Cadillac version" at Figure 18 warrants the higher costs and time delays. This is an example where higher point density (achieved with relatively minor cost increases) can reduce or eliminate the need for many expensive breaklines.

Figure 17. LiDAR mass points with nominal pulse spacing (NPS) of approximately 1 meter

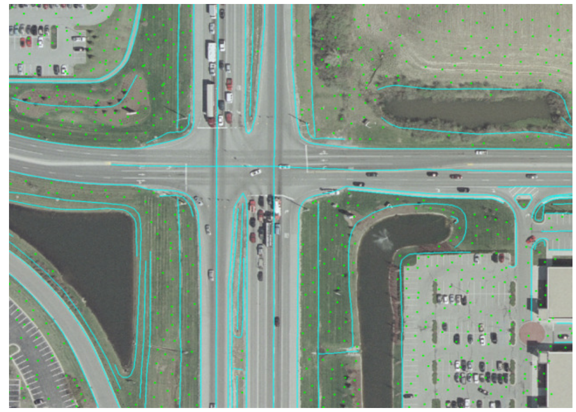


Figure 18. Thinned model key points and breaklines for swales, borrow pits with water, and road features

FAQ #7: How frequently does elevation data need to be updated?

If you think that topographic surfaces do not change with time, these examples may demonstrate otherwise.

Factors that Affect Hydraulic Analyses by FEMA. In assessing flood data update needs, FEMA requires an assessment of factors that affect hydraulic analyses (e.g., new bridges or culverts, new flood control structures, changes in stream morphology, coastal erosion) and factors that affect still water and wave height analyses for coastal flooding sources. Changes in stream morphology can be critical. Any significant change in the stream channel or floodplain geometry, particularly regarding the placement of fill, can affect the 1-percent-annual-chance floodplain and the associated regulatory floodway. Another consideration is any change in the stream location, either through natural processes (e.g., stream migration, erosion, or deposition) or through manmade changes (e.g., channelization, stream widening, stream straightening, or dredging). Additionally, any significant change in the vegetation or structural encroachments in the floodplain may affect a stream's hydraulic characteristics.

Analysis of Sea Level Change. Nearly every coastal State has requirements to predict the future impacts of sea level change, and credible predictions require accurate and current elevation data updated frequently. There is currently no "rule of thumb" to indicate the frequency of topographic/bathymetric data updates.

Management of Forests. LiDAR is used to map the changing heights of trees in America's forests. How frequently do foresters need to monitor changing forest metrics? For those who use LiDAR data to monitor forest health, how frequently do they need the LiDAR data to be updated in order to periodically monitoring the changing health of American forests? We hope this question can be answered as part of this questionnaire process. The ability to cut cross-sections through LiDAR point cloud data is vital for many assessments of changes in forest metrics.

Vegetation Encroachment. The North American Electric Reliability Corporation (NERC) has identified LiDAR as the best way to monitor the encroachment of vegetation on power lines, a major cause for widespread power outages.

Subsidence Monitoring. Digital elevation data are used to monitor land subsidence (Figure 19), the loss of surface elevation due to removal of subsurface support. Subsidence occurs in nearly every State in the U.S., including Florida where land have subsided between 1 and 2 feet, if not more. Subsidence is one of the most diverse forms of ground failure, ranging from small or local collapses to broad regional lowering of the earth's surface. The major causes of subsidence include: (1) dewatering of peat or organic soils, (2) dissolution in limestone aquifers, (3) first-time wetting of moisture deficient low density soils (known as hydro-compaction), (4) the natural compaction of soil, liquefaction, and crustal deformation, and (5) subterranean mining and withdrawal of fluids (petroleum, geothermal, and ground water).

Figure 19. Fifty years of subsidence (over 20 feet) in California's San Joaquin Valley. Image courtesy of National Geodetic Survey (NGS).

Subsidence has the following effects:

- Changes in elevation and gradient of stream channels, drains, and other water transporting facilities
- Damage to civil engineering structures – weirs, storm drains, sanitary sewers, roads, railroads, canals, levees, and bridges
- Structural damage to private and public buildings
- Failure of well casings from forces generated by compaction of fine-grained materials in aquifer systems
- In some coastal areas, subsidence has resulted in tidal encroachment onto lowlands

Agricultural Practices. In order to participate in USDA farm programs, Federal law requires that all persons that produce agriculture commodities must protect their highly erodible cropland from excessive erosion. In addition, anyone participating in USDA farm programs must certify that they have not produced crops on converted wetlands and did not convert a wetland. NRCS currently has numerous incentive programs (e.g., Stewardship Incentive Program (SIP), Emergency Watershed Protection (EWP) Program, Wildlife Habitat Incentives Program (WHIP), Cooperative Conservation Partnership Initiative (CCPI), Conservation Stewardship Program (CSP), Conservation Reserve Program (CRP) and Conservation Technical Assistance (CTA) Program), several of which encourage farmers to terrace their lands so as to retain water in the soil, rather than allow run-off of farm chemicals that pollute our streams. LiDAR offers the perfect remote sensing tool for broad-scale analyses of slopes and slope changes, as well as changes to wetlands, rangelands and habitat. Figures 20 through 23 demonstrate how LiDAR data, and slope derivatives, could be periodically compared to monitor changes in slopes and to evaluate successes or failures of such incentive programs. This example does not explain how often periodic updates are required, but it does demonstrate the need and benefit of periodic LiDAR data updates.

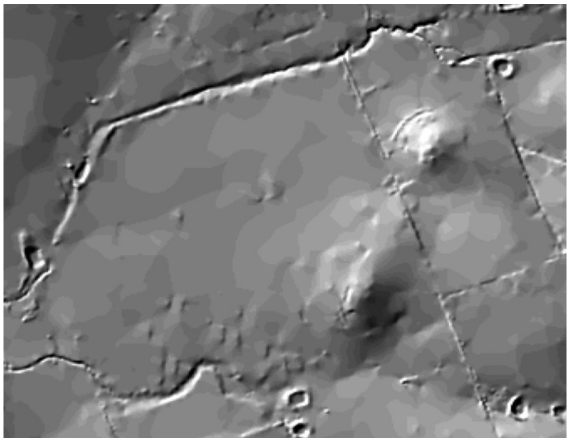


Figure 20. DEM hillshade prior to farm terracing

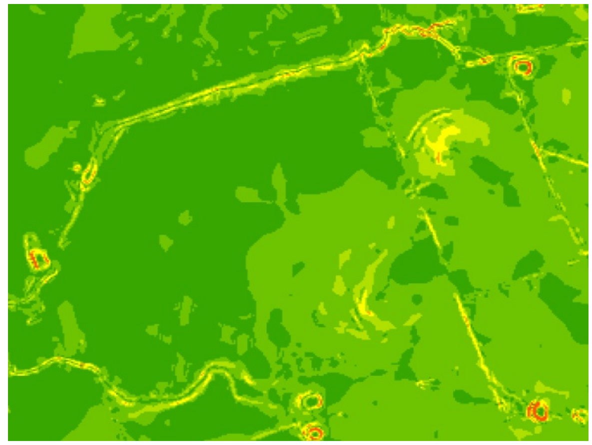


Figure 21. DEM slope gradient prior to farm terracing

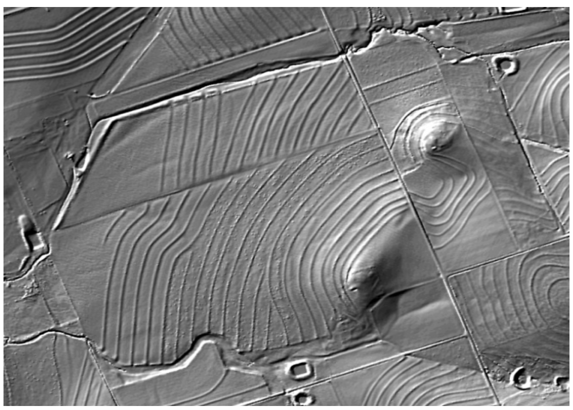


Figure 22. DEM hillshade after farm terracing

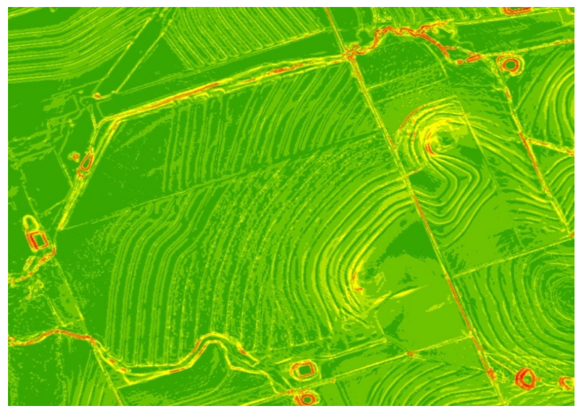


Figure 23. DEM slope gradient after farm terracing

NRCS personnel cannot personally visit every farm to validate which actions qualify for incentive programs, but periodic LiDAR updates allow for rapid assessments/comparisons of broad areas.

<u>Other Topographic Change Assessments</u>. Many other applications for digital elevation data require temporal change assessments of the changing topography, including: building/structure change analysis, changes to carbon stock estimates, changes to coastlines, debris flow monitoring, earthquake deformation metrics, changes to fire modeling and assessment, geologic/geophysical/seismic change analyses, geomorphic process monitoring, glacier change monitoring, habitat change assessment, landscape change analysis, landslide analysis, shoreline change monitoring, surface mining metrics, volcano metrics, urban modeling/change analysis, and wetland change analysis.

None of these are known to have established requirements for the frequency with which elevation datasets need to be updated, but these examples should help questionnaire respondents to understand that top reflective surfaces in Digital Surface Models (DSMs) and bare-earth Digital Terrain Models

(DTMs) change regularly by natural or manmade activities. As with digital orthophotos, elevation datasets also need to be periodically updated so that 3D surface analyses can be accurate and up-to-date for diverse user requirements.

FAQ #8: What are the standard 3DEP topographic LiDAR deliverables?

Raw (Full) Point Cloud: A *LiDAR point cloud* includes all first, intermediate and last returns from each laser pulse. When the first and last return elevations are the same, the laser pulse hit a hard feature such as the bare-earth terrain, concrete, asphalt, or perhaps a roof top. Figure 24 shows examples of a full point cloud in a forest. As shown in yellow, only a few of the first returns penetrated the vegetation to the ground. Some but not all of the second returns (blue) and third returns (red) penetrated to the ground. Only the lowest elevation returns at the bottom are used to produce the bare-earth DEM. First returns are used to produce the DSM.

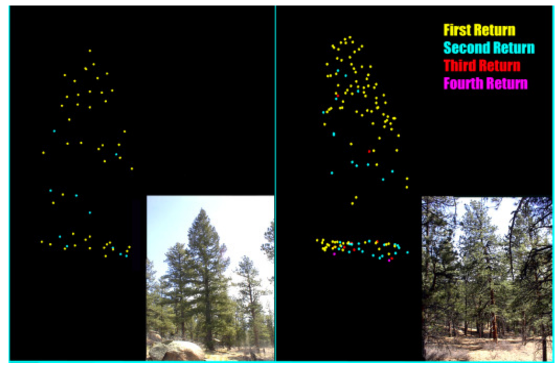


Figure 24. Examples of LiDAR point clouds on trees. Note the color-differences for 1st, 2nd, 3rd and 4th returns from each LiDAR pulse.

Classified Point Cloud: LiDAR point cloud data are subsequently processed to ASPRS LAS (laser file format) classes that distinguish between points on the ground, water, or elevated features such as buildings, trees, towers, bridges, etc. No points are discarded but may be classified as noise, or unclassified. All topographic LiDAR elevations in water are unreliable because sometimes the laser pulses are absorbed by the water, reflected from the water with differing intensities, or provide elevations on or below the level of the water surface.

Most topographic LiDAR datasets are flown with the laser scanning in a zig-zag pattern where the zigs and zags are so close that they appear to be parallel. The objective is to obtain pulse spacing and flight speed so that the nominal pulse spacing (NPS) is approximately equal in the in-flight and cross-flight directions.

Current ASPRS LAS classes are listed in Table 6. The minimum LAS classes for 3DEP topographic LiDAR datasets are classes 1, 2, 7, 9, 17, 18 and 20. Note also that class 20 was previously called class 10. Additional LAS classes for bathymetric or topobathymetric LiDAR include classes 40 through 45.

Table 6 – LAS Classes

Class Value	Meaning
0	Created, never classified
1	**Processed but unclassified, including undefined points such as unclassified vegetation**
2	**Bare-earth ground**
3	Low vegetation
4	Medium vegetation
5	High vegetation
6	Building
7	**Low point (noise)**

8	Model key points
9	**Water**
10	Rail
11	Road surface
12	Reserved
13	Wire – guard (shield)
14	Wire – conductor (phase)
15	Transmission tower
16	Wire-structure connector (e.g., insulator)
17	**Bridge deck**
18	**High noise**
20	**Ignored ground (near a breakline)**
21	Snow
40	**Bathymetric point (e.g., seafloor or riverbed; also known as submerged topography)**
41	**Water surface from bathy or topobathy LiDAR, distinct from Class 9 used for topo LiDAR**
42	**Derived water surface (synthetic water surface used in computing refraction at water level)**
43	**Submerged object, not otherwise specified (e.g., wreck, rock, submerged piling)**
44	**International Hydrographic Organization (IHO) S-57 object, not otherwise specified**
45	**No-bottom-found-at (bathy LiDAR point for which no detectable bottom return was received)**
46	**Top of Unconsolidated Material**
Others to 63	Reserved
64-255	User definable

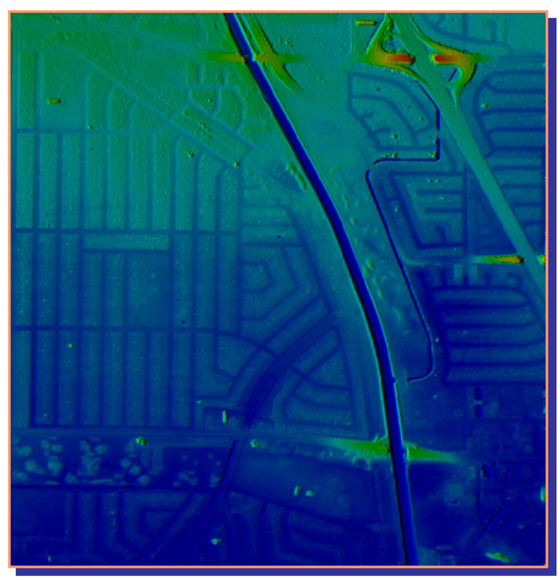


Figure 25. Digital Elevatiobn Model (DEM) is the bare-earth terrain, free of trees and manmade structures like buildings, bridges and towers. DEMs are gridded with uniform cell size.

Bare-earth surface, raster Digital Elevation Model (DEM): Whereas a Digital Terrain Model (DTM) is an elevation model of the bare earth terrain surface with irregularly-spaced points, a DEM is a raster (gridded) bare-earth surface with a uniform cell size. A bare-earth surface is free of trees, buildings, towers, bridges and other visible man-made features.

For the 3DEP, the DEM cell size is no greater than 2.5 feet and no less than the design Aggregate Nominal Pulse Spacing (ANPS). The 3DEP's DEM surface is hydro-flattened but not hydro-enforced (see below). Figure 25 shows an example of a bare-earth DEM. Compare with Figure 28 below.

A DEM for the 3DEP is hydro-flattened but not hydro-enforced.

Breaklines for standard hydro-flattening: The USGS Lidar Base Specification, V1.2 provides detailed guidance on breaklines for hydro-flattening, including inland ponds and lakes (≥2 acre surface area), dual-line streams and rivers (≥100 feet nominal width), non-tidal boundary waters, tidal water bodies, and islands (>1 acre).

Figure 26 shows a DEM that has been hydro-flattened with breaklines to make the lake shoreline level and to flatten the stream from bank-to-bank. Note that bridges have been cut, but unseen culverts have not been cut. Compare with Figure 29 below.

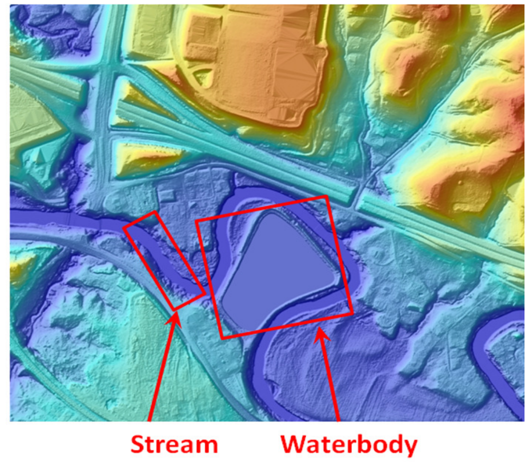


Figure 26. Example of a lake and stream that have been hydro-flattened with breaklines.

Hydro-flattening is a term used by USGS to explain how DEMs are processed for inclusion in the 3DEP. Hydro-flattening is performed to depict the bare-earth terrain as one could see and understand the terrain from an airplane flying overhead. The viewer would assume that the surfaces of lakes and reservoirs are flat and that rivers are flat from shore to shore. The viewer would also recognize that bridges are man-made features that should be removed from a bare-earth DTM because they are artificially elevated above the natural terrain.

Intensity Images: LiDAR also produces intensity images that record the intensity of return from each laser pulse. Intensity images are used with lidargrammetry for compilation of 3D breaklines. Figure 27 shows a sample LiDAR intensity image. The 3DEP requires intensity images to be produced for each tile to match the Classified LAS and DEM files. Images are 8-bit, 256 color gray scale in GeoTIFF format. Cell size is 2.5 feet.

Figure 27. Intensity image showing streaks over water from multiple flight lines. This is not a problem because topographic LiDAR measurements on water are already assumed to be unreliable and are classified separately as LAS Class 9.

Survey Control: The 3DEP requires ground control and check points that satisfy requirements specified in the ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014).

Metadata: The 3DEP requires metadata as detailed in the USGS Lidar Base Specification, V1.2.

Project Report: 3DEP LiDAR deliverables are accompanied with a Project Report which details a record of field work procedures; data derivation and adjustments; quality control procedures and results; problems encountered and solutions used in resolving such problems; statistical report summarizing the results of the airborne GPS adjustment and the overall accuracy of the adjusted IMU data.

FAQ #9: What are some of the more-common but non-standard LiDAR "buy-up" options?

Digital Surface Model (DSM): A DSM is a "top of canopy" or "top reflective surface" elevation model, including the bare earth in open terrain areas where there are no elevated features. A DSM includes the tops of buildings, trees, towers, and other features elevated above the bare earth. See Figure 28.

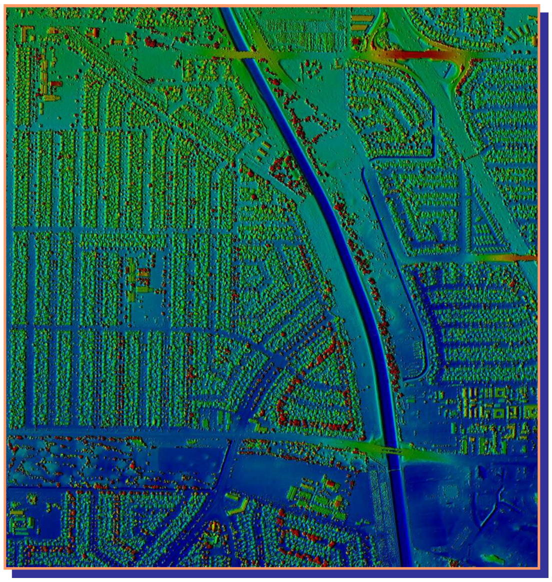


Figure 28. Digital Surface Model (DSM) includes treetops, rooftops, bridge decks, etc. Compare with Figure 25.

DSMs are typically gridded, as are DEMs, for more efficient file storage.

This "buy-up" option is relatively inexpensive because DSMs are easily produced from LiDAR "first returns" from the raw point cloud, and then gridded into a raster DSM.

LiDAR Waveform Data: LiDAR data in which the entire reflection of the laser pulse is fully digitized, captured, and stored. [Note: Standard discrete return LiDAR point clouds may already be extracted by LiDAR providers from full waveform LiDAR data during post processing for simplified user applications. Not all LiDAR systems are capable of digitizing the entire return signal. Discrete return LiDAR captures and stores the important peaks in the waveform data, each peak representing a return from a different target, discernible in vertical or horizontal domains.] LiDAR waveform datasets are much more demanding to store and process and require specialized software.

Hydro-Enforced Digital Terrain Model (DTM): *Hydro-enforcement* (Figure 29) includes hydro-flattening but adds steps for treatment of narrower dual- and single-line drains and culverts to enforce the downward flow of water.

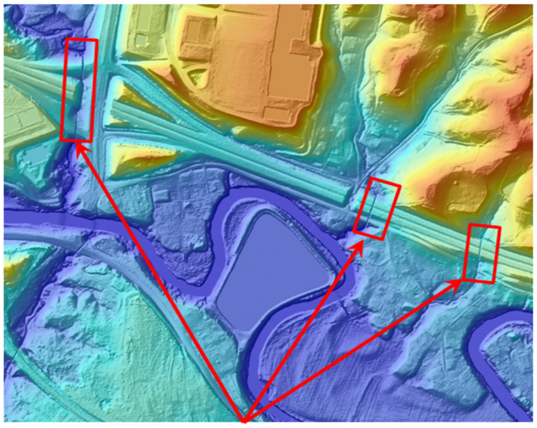


Figure 29. Hydro-enforcement uncovers below-ground culverts so that water will flow through in hydrologic and hydraulic models.

Hydro-enforcement is required for hydrologic modeling and management of watersheds and for hydraulic modeling of floodplains. It is also used for stormwater management.

Hydro-enforcement is much more expensive than hydro-flattening because a large amount of manual processing is required.

Figures 30 and 31 are commonly used as examples of how to hydro-enforce a dual-line stream that appears to block the flow of water in the TIN shown at Figure 30 but enforces the downward flow of water in the hydro-enforced TIN at Figure 31.

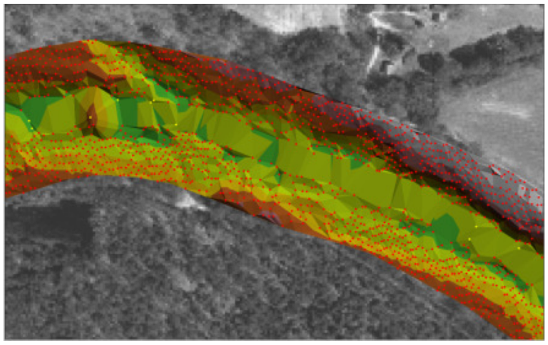


Figure 30. Rocks in the river, and/or natural undulating elevations along the shorelines, make the TIN appear as though water cannot pass downstream.

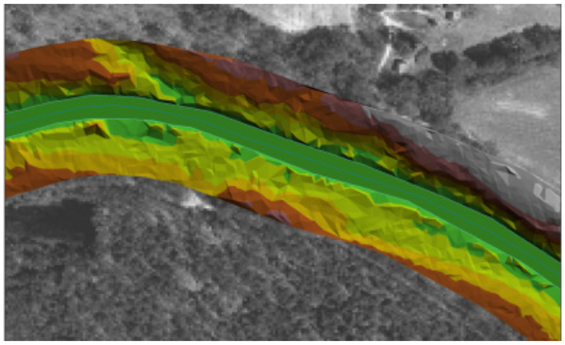


Figure 31. Breaklines for the dual shorelines are cut beneath the mapped elevations in order to hydro-enforce the flow of water; but this can create other problems.

There are no uniform standards for hydro-enforcement of below-ground culverts. For the National Flood Insurance Program (NFIP), FEMA leaves it up to the hydraulic engineer to determine when, where and how to hydro-enforce streams, bridges and culverts of all sizes. Figure 32 shows what happens when a culvert is not hydro-enforced, and Figure 33 shows what happens when a culvert is hydro-enforced.

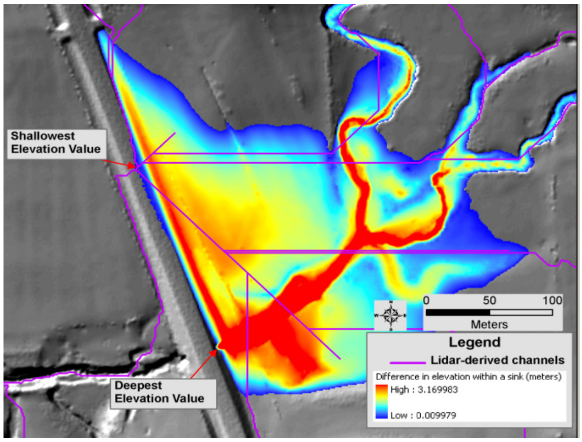


Figure 32. This shows what happens when the culvert is <u>not</u> hydro-enforced. In hydro models, the water flows in the ditch beside the road until it overflows the road at its shallowest elevation where the purple line crosses the road.

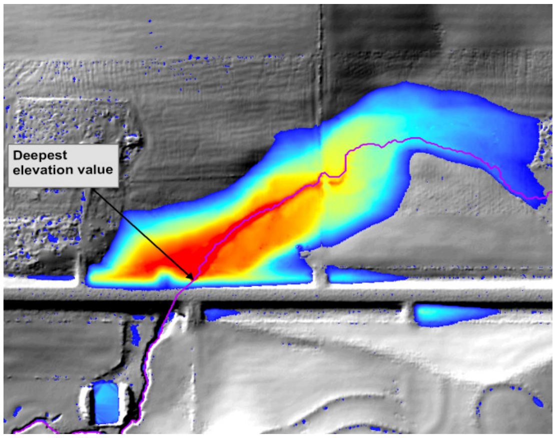


Figure 33. This shows a culvert "cut" to hydro-enforce the flow of water through this culvert. The darkest red shows the deepest part of the "puddle" and most likely location for the culvert entrance.

Puddles are one or more elevation posts totally surrounded by higher elevations. Figures 32 and 33 show puddles with red being the deepest part of each puddle. The puddles in these examples are suitable for hydro-enforcement, i.e., being "cut" and drained by culverts that are inferred but not absolutely known; a "cut" is shown in Figure 32 with the purple connector line that crosses the road. Figure 6 (see FAQ #5) shows dry puddles that should not be hydro-enforced; it is ideal when drainage features can be mapped when they are dry. Limestone sinks and dry swimming pools are other types of puddles that should not normally be drained by hydro-enforcement.

2-D or 3-D Building Footprints. FAQ #6, Figure 15 shows how 2-D or 3-D building footprints can be derived from LiDAR datasets. The process is semi-automated but requires additional processing to create smooth roofline edges. 2-D footprints have x/y coordinates only whereas 3-D footprints typically show the highest elevation of any feature on the rooftop. Digital orthophotos are sometimes used to digitize 2-D building footprints but the building positions are distorted because of "building lean" from elevated features, often causing roofs to appear to overlay sidewalks and streets.

Enhanced Breaklines: There are many forms of enhanced breaklines that can become quite expensive to produce, to include the following:

- Narrower double-line streams and rivers (compared with 100'-wide streams for the 3DEP)
- Smaller ponds (compared with 2 acre ponds in the 3DEP)
- Single-line drains for hydro flow lines
- Road edge-of-pavement
- Curbs and gutters
- Retaining walls
- Underground culverts

Power Lines and Towers: It is common for electric utilities to map their power lines and towers with LiDAR and compare with encroaching vegetation, also mapped with LiDAR, for electric reliability purposes. See Figure 34.

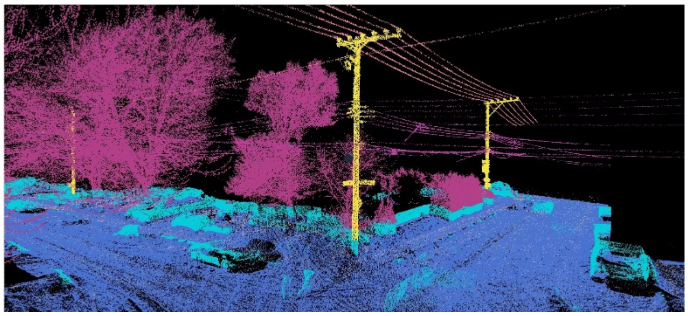


Figure 34. Power lines, poles and towers mapped with LiDAR.

Low Confidence Areas (ASPRS): With photogrammetry, it was traditional to use dashed contour lines when the photogrammetrist could not see the bare earth in stereo (normally in forested areas) to compile contour lines. Section C.8 of the ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) states:

"Low confidence areas also occur with LiDAR where heavy vegetation causes poor penetration of the LiDAR pulse. Although costs will be slightly higher, ASPRS recommends that "low confidence areas" for LiDAR be required and delivered as two-dimensional (2D) polygons based on the following four criteria:

1. Nominal ground point density (NGPD);
2. Cell size for the raster analysis:
3. Search radius to determine average ground point densities; and
4. Minimum size area appropriate to aggregate ground point densities and show a generalized low confidence area (minimum mapping unit).

"This approach describes a raster-based analysis where the raster cell size is equal to the Search Radius listed for each Vertical Data Accuracy Class. Raster results are to be converted into polygons for delivery.

“This section describes possible methods for the collection or delineation of low confidence areas in elevation data sets being created using two common paradigms. Other methodologies currently exist, and additional techniques will certainly emerge in the future. The data producer may use any method they deem suitable provided the detailed technique is clearly documented in the metadata.

“Table C.2lists the values for the above low confidence area criteria that apply to each vertical accuracy class.

Table C.2 Low Confidence Areas (abbreviated)

Vertical Accuracy Class	Recommended Project Min NPD (pts/m^2) (Max NPS (m))	Recommended Low Confidence Min NGPD (pts/m^2) (Max NGPS (m))	Search Radius and Cell Size for Computing NGPD (m)	Low Confidence Polygons Min Area (acres (m^2))
5-cm (QL0)	8 (0.35)	2 (0.71)	1.06	2 (8,000)
10-cm (QL1/QL2)	2 (0.71)	0.5 (1.41)	2.12	5 (20,000)

“Low confidence criteria and the values in Table C.2 are based on the following assumptions:

- “**Ground Point Density**: Areas with ground point densities less than or equal to ¼ of the recommended nominal pulse density (pulse per square meter)or twice the nominal pulse spacing are candidates for Low Confidence Areas. For example: a specification requires an NPS of 1 meter (or an NPD of 1 ppsm) but the elevation data in some areas resulted in a nominal ground point density of 0.25 points per square meter (nominal ground point spacing of 2 meters). Such areas are good candidates for “low confidence” areas.
- “**Raster Analysis Cell Size**: Because the analysis of ground point density will most likely be raster based, the cell size at which the analysis will be performed needs to be specified. The recommendation is that the cell size equals the search radius.
- **“Search Radius for Computing Point Densities**: Because point data are being assessed, an area must be specified in order to compute the average point density within this area. The standards recommend a search area with a radius equal to 3 * NPS (*not the Low Confidence NGPS*). This distance is small enough to allow good definition of low density areas while not being so small as to cause the project to look worse than it really is.
- **“Minimum Size for Low Confidence Polygons**: The areas computed with low densities should be aggregated together. Unless specifically requested by clients, structures/buildings and water should be removed from the aggregated low density polygons as these features are not true Low Confidence.

“Aggregated polygons greater than or equal to the stated minimum size as provided in Table C.2 should be kept and defined as Low Confidence Polygons. In certain cases, too small an area will “checker board” the Low Confidence Areas; in other cases too large an area will not adequately define Low Confidence Area polygons. These determinations should be a function of the topography, land cover, and final use of the maps.

"Acres should be used as the unit of measurement for the Low Confidence Area polygons as many agencies (USGS, NOAA, USACE, etc.) use acres as the mapping unit for required polygon collection. Approximate square meter equivalents are provided for those whose work is exclusively in the metric system. Smoothing algorithms could be applied to the Low Confidence Polygons, if desired.

"There are two distinctly different types of low confidence areas:

- "The first types of low confidence areas are identified by the data producer – *in advance* – where possible identification of the bare earth is expected to be unlikely or impossible. These are areas where no control or checkpoints should be located and where contours, if produced, should be dashed. They are exempt from accuracy assessment. Mangroves, swamps, and inundated wetland marshes are prime candidates for such advance delineation.
- "The second types of low confidence areas are valid VVA areas, normally forests that should also be depicted with dashed contours, but where checkpoints *should* be surveyed and accuracy assessment *should* be performed. Such low confidence areas are delineated subsequent to classification and would usually be identifiable by the notably reduced density of bare-earth points.

"Providing Low Confidence Area polygons allows LiDAR data providers to protect themselves from unusable/unfair checkpoints in swamps and protects the customer from data providers who might try to alter their data.

"If reliable elevation data in low confidence areas is critical to a project, it is common practice to supplement the remote sensing data with field surveys."

Low Confidence Areas (Florida):

In Florida swamplands with mangrove, sawgrass and other dense vegetation, it is common for LiDAR last returns to fail to penetrate to the ground (see Figures 35 and 36).

Figure 35. An area of Florida swampland

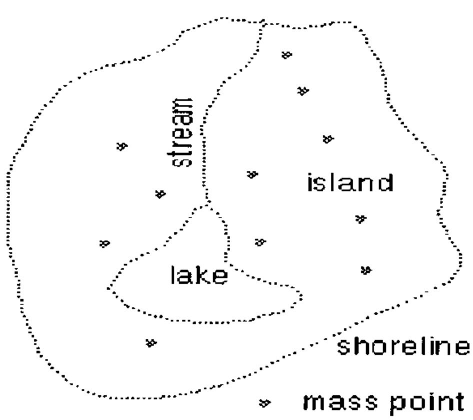
Figure 36. Zoomed-in area where LiDAR did not penetrate to the ground. Red areas are over 6' taller than surroundings

When no ground points exist in the LiDAR point cloud, automated ground routines will classify the lowest vegetation points as ground, effectively including vegetation in the bare earth surface models Typically, vegetation classified as ground whose height (compared to surrounding confirmed bare-earth terrain) is at or below the Vegetated Vertical Accuracy (VVA) threshold will be allowed to remain in the ground whereas all other vegetation classified as ground whose height exceeds the VVA threshold will be reclassified from ground to another appropriate class. For example, in a project requiring 10 cm RMSEz, the VVA threshold is 30 cm. Any vegetation classified as ground whose height is 30 cm (1 foot) or less could remain in the bare-earth surface but all other vegetation classified as ground whose height is greater than 30 cm would be reclassified and removed from the bare earth surface (LAS Class 2). Using the VVA threshold for allowance of vegetation in the ground removes high vegetation from the bare earth surface, which can have a negative impact on its usability, but reduces the amount of ground voids in a dataset and reduces the manual edit time required by allowing low vegetation to remain in the dataset. The low vegetation remaining in ground is less impactful to the overall usability of the dataset.

Automated or Manual Low Confidence Area Polygons. Low confidence area polygons can be derived in an automated fashion to identify areas of poor LiDAR penetration IF the vegetation has been reclassified out of ground (other than LAS class 2). Automated low confidence polygons use the density of the ground classification to identify areas of low ground density and areas of ground voids. Automated low confidence polygons will not identify areas of low vegetation classified as ground as these areas typically have a sufficient density to be excluded from low density thresholds used to define low confidence areas. If all vegetated areas, including low vegetation allowed to remain in the ground classification, must be identified with low confidence polygons, a manual (higher cost and increased production time) process will be required.

FAQ #10: What "LiDAR derivatives" are typically produced by users from standard "LiDAR deliverables"?

Triangulated Irregular Network (TIN): A TIN is a set of adjacent, non-overlapping triangles computed from mass points and/or breaklines. Figure 38 shows how the TIN was generated from the mass points and breaklines in Figure 37. The TIN's vector data structure is based on irregularly-spaced point, line and polygon data interpreted as mass points and breaklines and stores the topological relationship between triangles and their adjacent neighbors.



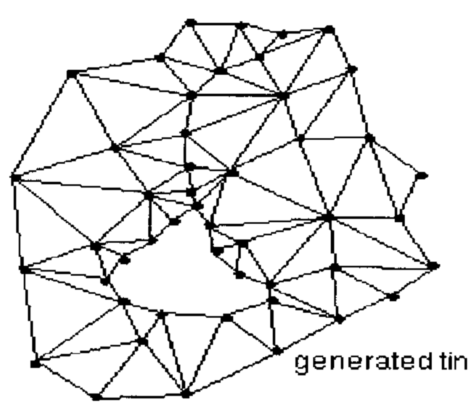


Figure 37. Example mass points and breaklines

Figure 38. TIN produced from these mass points and breaklines

Esri Terrain: An ESRI *Terrain* is a multi-resolution, TIN-based surface built on-the-fly from feature classes stored in a feature dataset of a geodatabase. Terrain datasets are more effective for storing and visualizing large point data sets. A Terrain dataset resides in the same feature dataset where the feature classes (used to construct it) reside. Terrain datasets can be used to obtain TINs and grids.

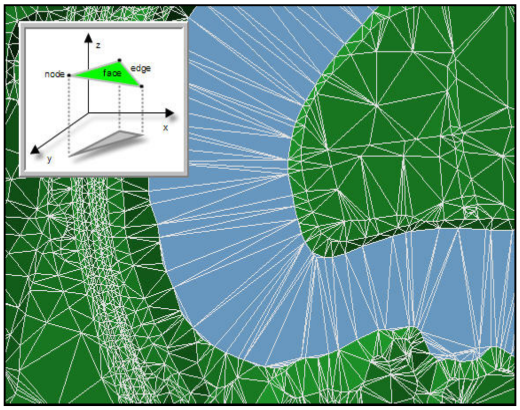


Figure 39. Example of a Terrain showing TIN triangles.

As shown at Figure 39, a Terrain is composed of a series of TINs, each of which is used within a map-scale range. For each map-scale range, a level of detail (i.e., z-resolution) and pyramid level are defined. The Terrain establishes a set of user-defined viewing pyramid levels, each having fewer participating source points as the user zooms to smaller scales. Unlike an ESRI Grid or DEM file, the Terrains are generated by utilizing the actual surface points rather than interpolated elevation values for a cell in a raster file. This data storage and visualization method enables faster viewing of large area Terrains at small scales – easier than most other elevation data types.

Figures 40, 41 and 42 show examples of a DEM with 2-meter post spacing/cell size, and when "intelligently-thinned" at two user-defined Terrain pyramid levels.

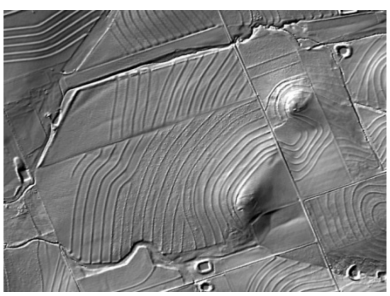


Figure 40. DEM displayed with full 2-meter DEM post spacing/cell size

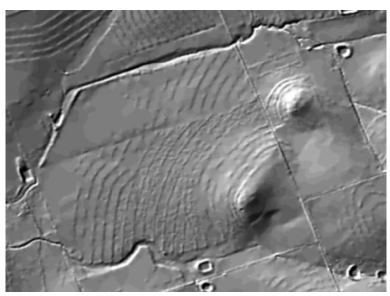


Figure 41. Terrain Pyramid Level 1, 5-meter cell size, 1/4 meter Z-tolerance

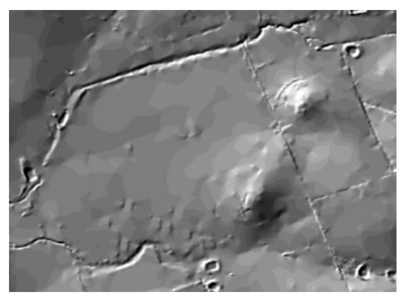


Figure 42. Terrain Pyramid Level 2, 5-meter cell size, 1/2 meter Z-tolerance

Contours: Both contours and hillshades are LiDAR derivative products that help users visualize the terrain in three dimensions.

Contour lines are isolines that depict equal elevation on a surface. They are primarily used for 2D human interpretation of the 3D terrain surface. Figure 43 shows a contour map with 2' contour interval, meaning that the RMSEz should be ≤8" (one third the contour interval). With modern GIS technology, contours can be generated with the push of a button from LiDAR datasets, but users can be easily misled if the contour interval is less than three times RMSEz making the contours appear to be more accurate than they really are.

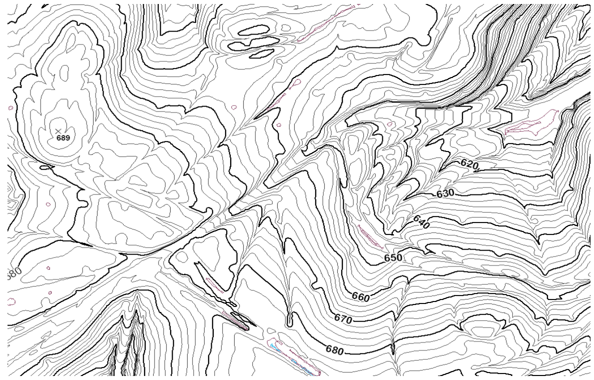


Figure 43. This is an example of a contour map with 2' contour interval, with index contours at 10' intervals.

Hillshades: Hillshades have replaced contour lines as the best way to visualize 3-D topographic surfaces. Viewing angles and sun angles can be varied to maximize visual interpretability of the terrain, as shown in Figures 44 and 45. They normally use a color elevation ramp, but some hillshades are black and white.

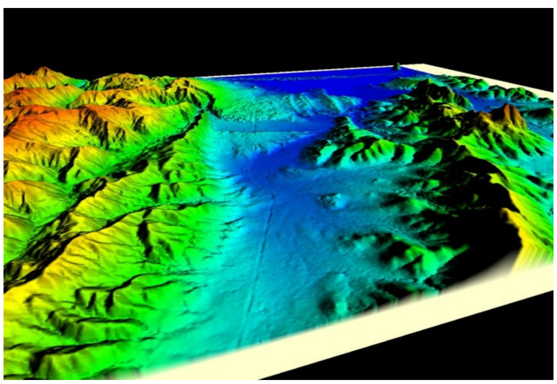


Figure 44. Hillshade with 45°sun angle and 45° azimuth.

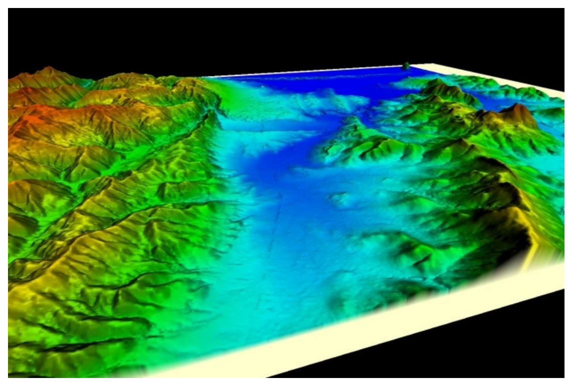


Figure 45. Hillshade with 70° sun angle and 70° azimuth.

Figure 46 shows how the B/W hillshade supplements the orthophoto in Figure 47.

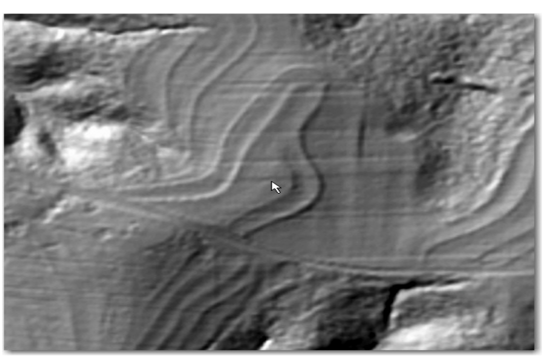


Figure 46. Hillshades in black and white are also effective in visualization of the 3D topographic surface.

Figure 47. Color orthophoto doesn't reveal topographic characteristics clearly visible in the prior figure.

Slope and Aspect Maps:

Derived from TINs, slope and aspect are the other two most common elevation derivatives used in many computer models.

Figure 48 shows a simple hillshade of ridge lines and surrounding hills.

Figure 49 shows a slope map where red areas are the steepest and green areas are the flattest.

Figure 50 shows an aspect map of the same area where the hottest colors are facing the sun and the coolest colors are facing away from the sun.

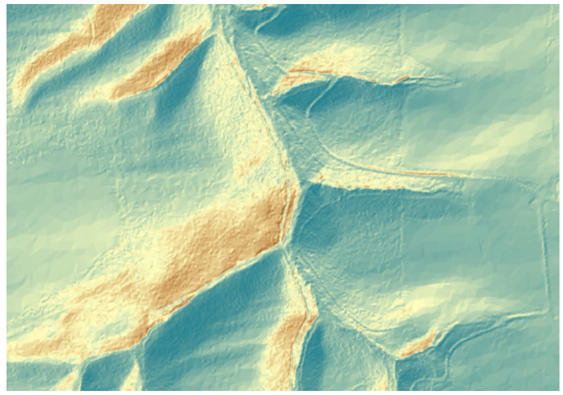


Figure 46. Hillshade of ridge and hills.

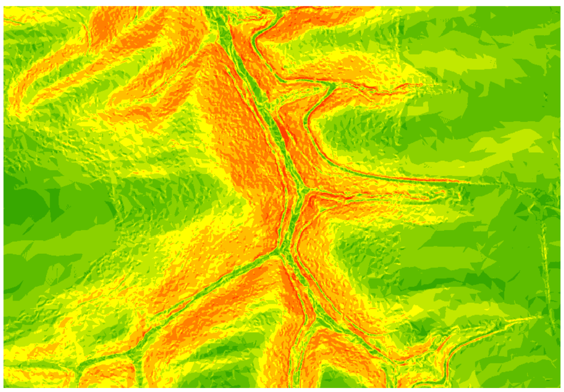


Figure 49. Color-coded slope map of ridge and hills.

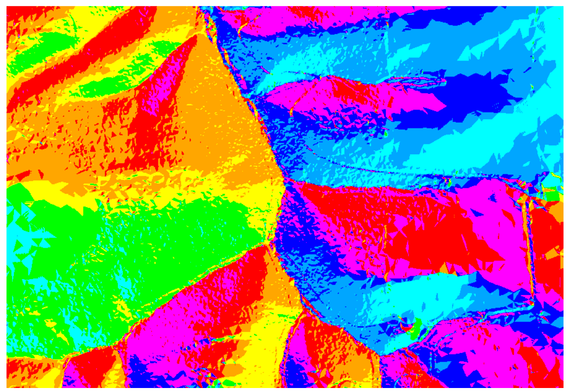


Figure 50. Color-coded aspect map of ridge and hills

Curvature Maps. As demonstrated in Figures 51 and 52, curvature is another elevation derivative, commonly used in applications that determine the soil wetness index. Slope, aspect and curvature, all elevation derivatives, are the leading parameters used in definition of soils classifications by the Natural Resources Conservation Service (NRCS). These elevation derivatives are relevant also to the hydrologic and hydraulic modeling community and forestry, agriculture and construction industries where slope and surface drainage are important.

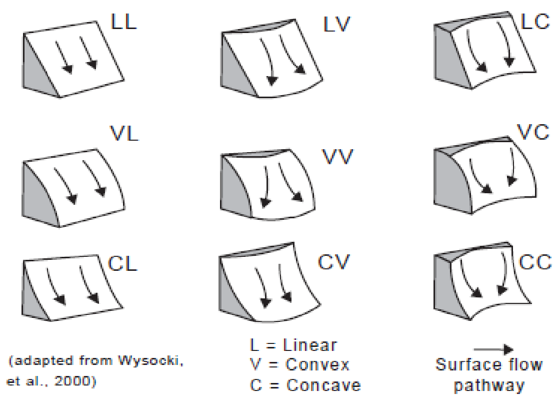


Figure 51. Curvature types

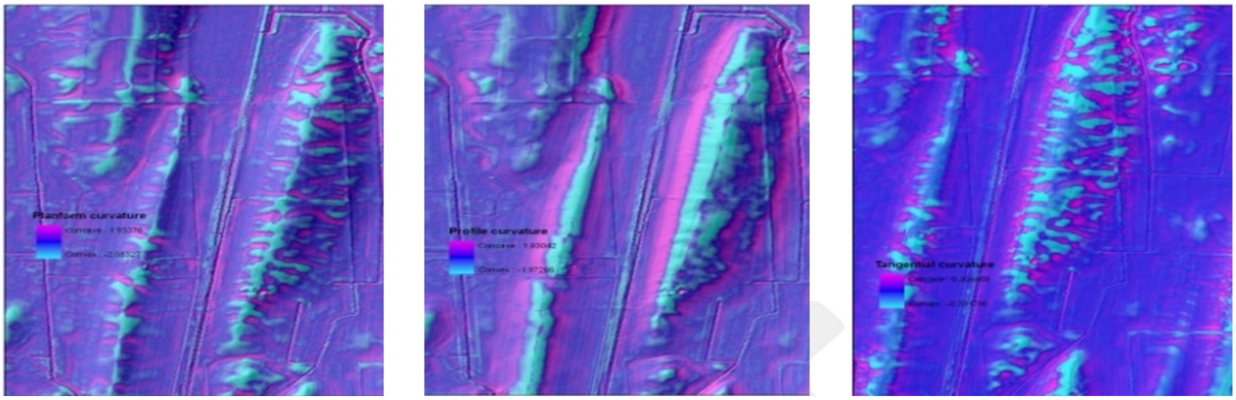


Figure 52. Plan form curvature (left); profile curvature (center); tangential curvature (right) generated from ESRI software.

Cross Sections: *LiDAR cross-sections*, also called *transects,* are profiles "cut" through LiDAR point clouds in order to visualize or measure heights or elevation differences in points collected along those cross-sections. Figure 53 shows an example of a LiDAR cross-section cut across a river, to include elevation data on a bridge as well as elevations of bare-earth terrain, vegetation and buildings on either side of the river.

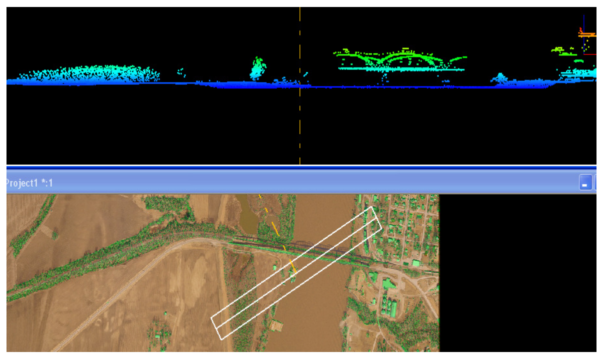


Figure 53. Digital orthophoto (lower image) shown with location of cross-section cut in LiDAR data. The upper image shows the elevations of all features along this cross-section.

FAQ #11: The questionnaire refers to tide-coordination, MHW and MLLW. What is the significance of these terms?

Some organizations choose to pay extra for tide-coordinated LiDAR data acquisition, for example, by specifying that topographic LiDAR be acquired with water levels at or below Mean Lower Low Water (MLLW) to expose more land that is not submerged, and/or by specifying that topobathymetric LiDAR be acquired with water levels at or above Mean High Water (MHW) or Mean Higher High Water (MHHW_ to map more water depths that are submerged. This combination enables the tidelands to be mapped both ways, making it easier to seamlessly merge topographic and bathymetric data across the tidelands by establishing seamlines where the two datasets agree on common elevations after NOAA's Vertical Datum Transformation Tool (VDatum) is used to transform bathymetric data from a tidal datum to NAVD88.

Figure 54 shows why MHW and MLLW are especially relevant to Florida. The Mean High Water (MHW) line is the boundary between privately-owned uplands and state submerged lands. Mean Lower Low Water (MLLW) defines the chart datum, the level of water that charted depths displayed on a nautical chart are measured from.

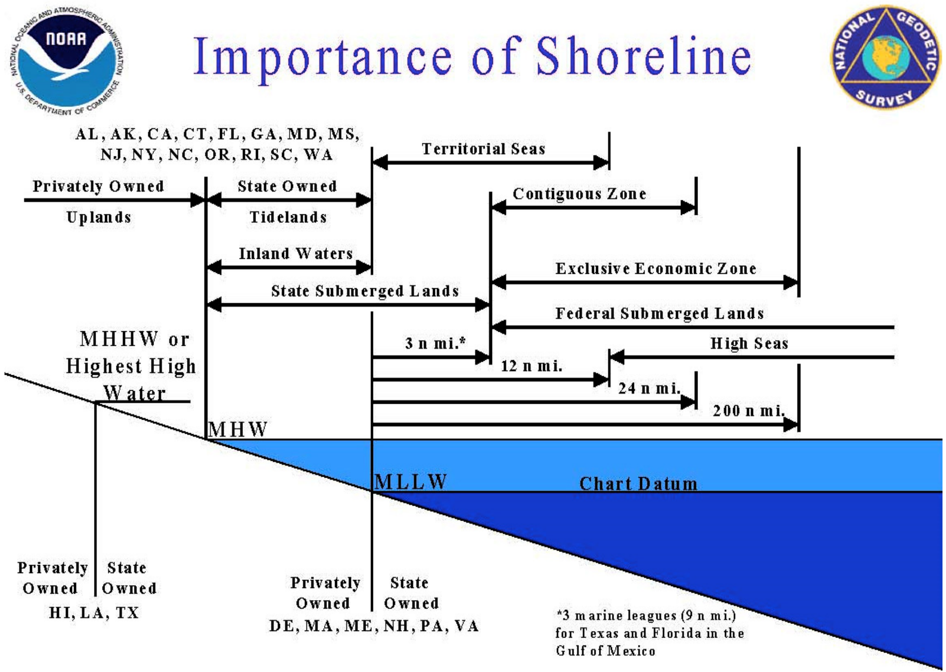


Figure 54. In Florida, MHW defines the official shoreline that separates privately owned uplands from state-owned tidelands, inland waters and state submerged lands. The MLLW not only establishes the chart datum for U.S. waters, but MLLW establishes territorial seas and distances (9 n. mi. in Florida) to the beginning of the Exclusive Economic Zone and Federal Submerged Lands, for example.

Mean Higher High Water (MHHW). MHHW is defined as the arithmetic mean of the higher high water heights of the tide observed over a specific 19-year Metonic cycle denoted as the NTDE. Only the higher high water of each pair of high waters of a tidal day is included in the mean.

Mean High Water (MHW). MHW is defined as the arithmetic mean of the high water heights observed over a specific 19-year Metonic cycle.

Mean Sea Level (MSL). MSL is defined as the arithmetic mean of hourly heights observed over a specific 19-year Metonic cycle.

Mean Low Water (MLW). MLW is defined as the arithmetic mean of the low water heights observed over a specific 19-year Metonic cycle.

Mean Lower Low Water (MLLW). MLLW is defined as the arithmetic mean of the lower low water heights of the tide observed over a specific 19-year Metonic cycle. Only the lower low water of each pair of low waters of a tidal day is included in the mean.

FAQ #12: What are your requirements for nautical charting?

NOAA's in-house and contract surveys that are done mostly in channels are required to be conducted to the appropriate International Hydrographic Organization (IHO) S 44 standards (2008), which defines two types of surveys to be used in ports, harbors, and shallow channels: Special Order and Order 1a. These standards require both full sea floor search and object detection of submerged objects. Multibeam sonar and/or sidescan sonar surveys are used to meet these standards in water depths greater than 4-10 m; topobathymetric LiDAR and sidescan sonar are used in 0-15 m depths. In general single-beam sonar surveys alone cannot meet these standards because they do not provide full sea floor search or object detection.

As part of the IWG-OCM National Coastal Mapping Strategy initiative, NOAA and USACE are now introducing bathymetric LiDAR Quality Levels, with variable point densities and depth-dependent depth accuracies, compliant with IHO Special Order and less-demanding Order 1 standards. If you need to detect submerged objects (> 1 m^3) for nautical charting, you will need either $QL0_B$ or $QL2_B$ bathymetric or topobathymetric LiDAR explained in FAQ #6, Table 4, above.