Appendix A – Frequently Asked Questions (FAQs)

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It is important for respondents to the questionnaire to understand the answers to the 17 FAQs explained, with graphic examples, below. The terms explained herein must be understood in order to provide valid responses to questions pertaining to user elevation data requirements and benefits.

FAQ #1: What are mass points, breaklines, TINs, and Terrains?

Mass points are irregularly-spaced elevation points, each with an x/y location and z-value (3-D coordinates). They could be sparsely-populated spot heights generated manually from photogrammetry and deliberately placed to depict elevations of prominent features representing highest or lowest elevations in an area, as shown in Figure 1; however, *mass points* more commonly refer to densely-populated points with 3-D coordinates generated by automated methods, e.g., by LiDAR or IFSAR scanners or photogrammetric auto-correlation techniques.

Breaklines are linear features that describe a change in the smoothness or continuity of a surface. Breaklines can be either 2-D breaklines with x/y coordinates only (longitude/latitude or Easting/Northing) or 3-D breaklines with x/y coordinates plus z-values representing elevations above a defined vertical datum, normally NAVD88. Figure 1 shows example breaklines for the shoreline of an island, for the shoreline of an inland lake on that island, and for a stream that potentially drains water from the lake into the ocean surrounding the island.

A *Triangulated Irregular Network (TIN)* is a set of adjacent, non-overlapping triangles computed from mass points and/or breaklines. Figure 2 shows how the TIN was generated from the mass points and breaklines in Figure 1. 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.

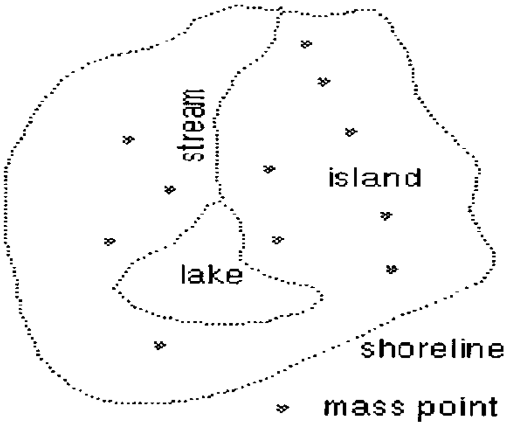

Figure 1. Example mass points and breaklines

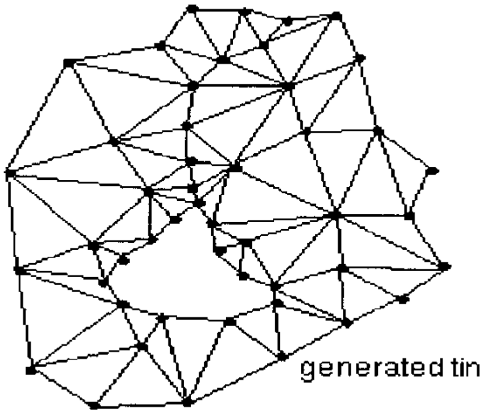

Figure 2. TIN produced from these mass points and breaklines

An ESRI *Terrain* is a multi-resolution, TIN-based surface build 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.

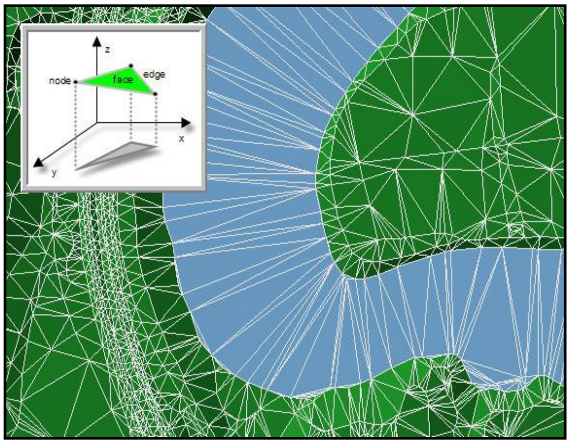

Figure 3. Example of a Terrain showing TIN triangles.

As shown at Figure 3, 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 4, 5 and 6 show examples of a DEM with 2-meter post spacing/cell size, and when “intelligently-thinned” at two user-defined Terrain pyramid levels.

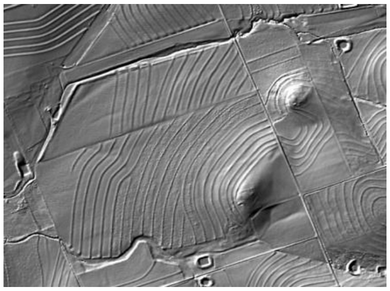

Figure 4. DEM displayed with full 2-meter DEM post spacing/cell size

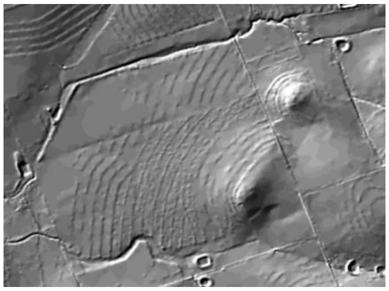

Figure 5. Terrain Pyramid Level 1, 5-meter cell size, 1/4 meter Z-tolerance

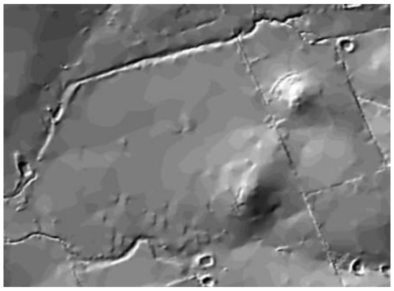

Figure 6. Terrain Pyramid Level 2, 5-meter cell size, 1/2 meter Z-tolerance

Today, some combination of mass points, breaklines, TINs and/or Terrains are used to produce DEMs.

FAQ #2: What are digital elevation models (DEMs)?

As used in this questionnaire, a Digital Elevation Model (DEM) is a grid of bare-earth z-values at regularly spaced intervals in x and y directions. For national datasets, x and y may be best defined on a spherical reference surface in terms of longitude and latitude. For smaller datasets, x and y are normally defined on a planar (flat) reference surface, normally using Universal Transverse Mercator (UTM) or State Plane coordinates. For entry into the NED, USGS converts data with UTM or State Plane coordinates into DEMs with arc-second post spacing. **Whereas traditional contours are still used by some for manual, visual interpretation of the topographic surface, today’s DEMs are widely used for a large variety of automated analyses, mathematical models, and 3D simulations and visualizations.**

For DEMs in the NED, DEM post spacing (grid spacing) is defined in geographic coordinate angular units on a spherical surface. Figure 7 shows Δx and Δy in arc-seconds of longitude and latitude, best for a national dataset with multiple “nested” resolutions as used with the National Elevation Dataset (NED).

For smaller elevation datasets produced for states and counties for example, DEM post spacing is normally alternatively defined in metric units on a planar surface. Figure 8 shows Δx and Δy in meters for either UTM or State Plane Coordinate System (SPCS) georeferencing.

Originally, DEMs were interpolated from contours; but today, most contours are produced from DEMs, supplemented with breaklines to make them aesthetically pleasing, as shown at Figure 9. Today's DEMs are produced from LiDAR, stereo imagery, or IFSAR.

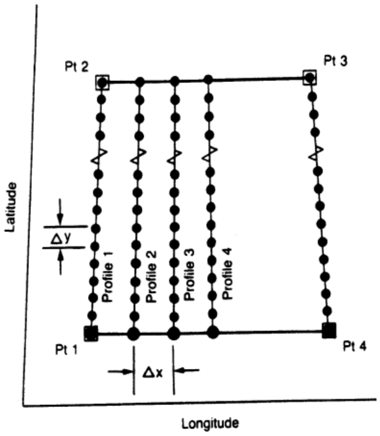

Figure 7. Δx and Δy in arc-seconds of longitude and latitude used w/NED

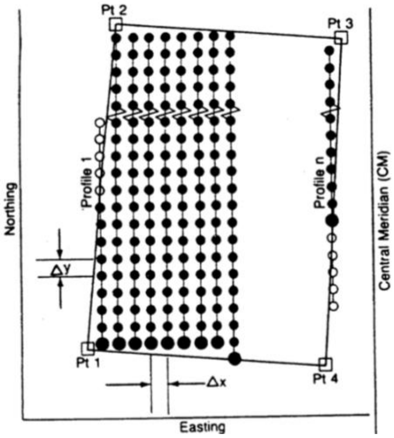

Figure 8. Δx and Δy in feet or meters used w/UTM or State Plane system

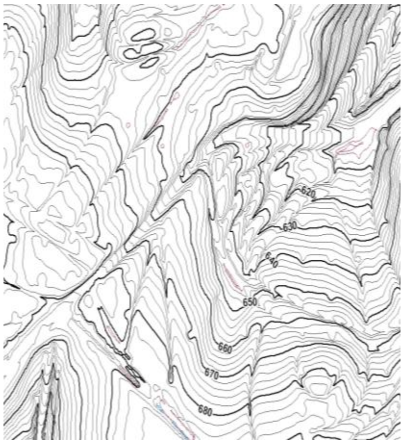

Figure 9. Contours produced from DEM using hydro and road breaklines

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 10. DEMs have small file sizes because x/y incrementation by Δx and Δy eliminates the need for storing individual x/y coordinates, as shown at Figure 11.

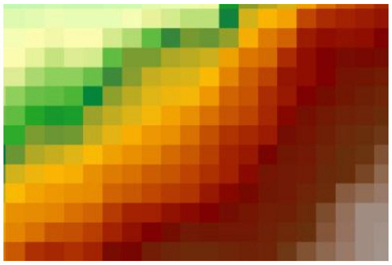

Figure 10. DEM viewed as pixels, color-coded by elevation

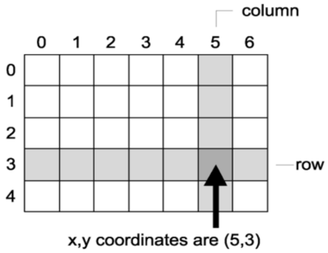

Figure 11. DEM files are small and efficient because individual x/y coordinates do not need to be stored

FAQ #3: What is the difference between a digital terrain model (DTM) and a digital surface model (DSM)?

A Digital Terrain Model (DTM) is an elevation model of the bare earth terrain surface, but normally with irregularly-spaced points rather than the uniform grid structure of a DEM. A DTM often includes breaklines to help define edges of TIN triangles. See bottom of Figure 12. A hydro breakline could be added here to enforce the downward flow of water in the drainage feature.

A Digital Surface Model (DSM) is an elevation model of the top reflective surface, including the bare earth in open terrain areas, as well as the tops of buildings, trees, towers, and other features elevated above the bare earth. See top of Figure 12.

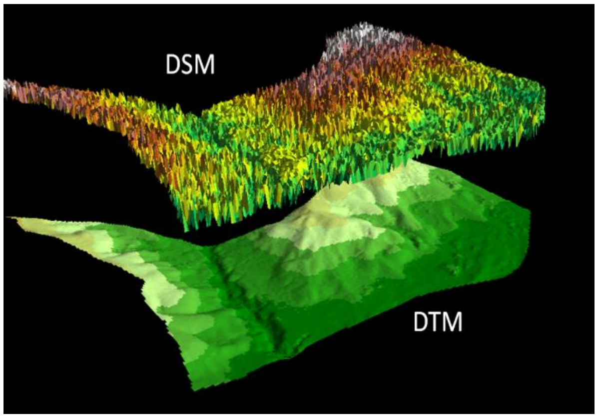

Figure 12. DSM of top reflective surface and DTM of bare-earth terrain beneath the vegetation.

FAQ #4: What is the difference between a DTM and a TIN?

A Digital Terrain Model (DTM) generally refers to an irregular surface of elevations represented with discreet masspoints measured by LiDAR or photogrammetric means and may also contain vector breaklines. A DTM is generally represented in a vector, ascii or binary format. DTMs are easily tiled within exact tile boundaries.

A Triangulated Irregular Network (TIN) is a data structure used to represent a ground surface model like a DEM or DTM. A TIN usually contains the same masspoints and/or breaklines as a DTM. However, the TIN data structure also contains a topological component by which discreet points and vertices are connected through a series of triangles, each triangle having its own slope and aspect. Each triangle creates a unique facet in the ground surface model and these facets are extremely useful for visualizing and analyzing slope, aspect, cut and fill of the terrain, and they are used for interpolation of gridded elevation posts and for generation of contours. A TIN's file size is normally between 2X and 4X larger than a DTM covering the same area with the same masspoints and breaklines. It is more difficult to tile a TIN because TIN triangles normally cross over tile boundaries.

Figure 13 shows a geometric view of TIN triangles; each triangle maintains topological data structure with all adjoining TIN triangles. Figure 14 shows a surface view of this TIN, with interpolated contours. Each TIN triangle has its own slope and aspect. These triangles are interpolated at X/Y coordinates of DEM posts to determine the elevation of each post; a DTM cannot do this. TIN triangles are also interpolated to determine contour lines of equal elevation that cross these TIN triangles; a DTM cannot do this either.

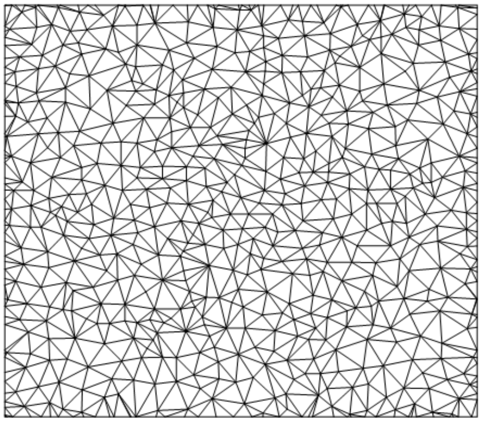

Figure 13. Geometric view of TIN with topological data structure, showing individual TIN triangles

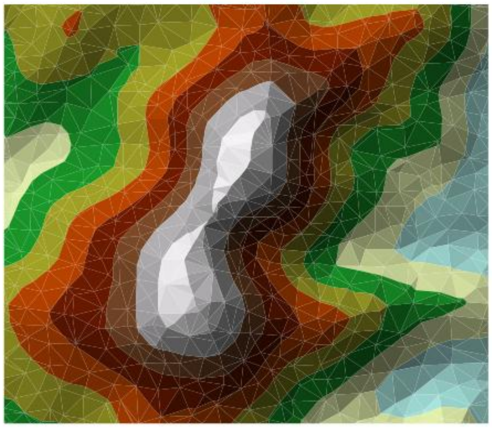

Figure 14. Surface view of TIN with derived contours. DEM elevation posts are interpolated from TIN triangles

FAQ #5: How are DEMs produced from imagery/photogrammetry, IFSAR and LiDAR?

Gridded DEMs are produced at mathematically-computed x and y coordinates by interpolation on TIN triangles produced from irregularly-spaced mass points surrounding each point to be interpolated. The most important points to understand about these technologies are the following:

Photogrammetry

Photogrammetry requires stereo views of the terrain from two different perspectives. If both views cannot see the bare earth terrain beneath the trees, then photogrammetry cannot map the elevations of the bare earth. This is why photogrammetry is well suited for open terrain but ill suited for mapping of vegetated areas. Figures 15 and 16 shows how stereo views are obtained from traditional frame cameras (digital and film) and from new push-broom sensors.

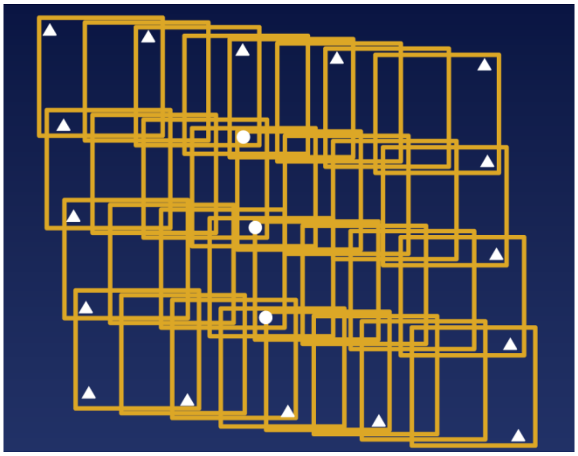

Figure 15. Frame cameras (digital and film) obtain stereo images by having at least 60% overlap between photos so that all areas are imaged from two perspectives

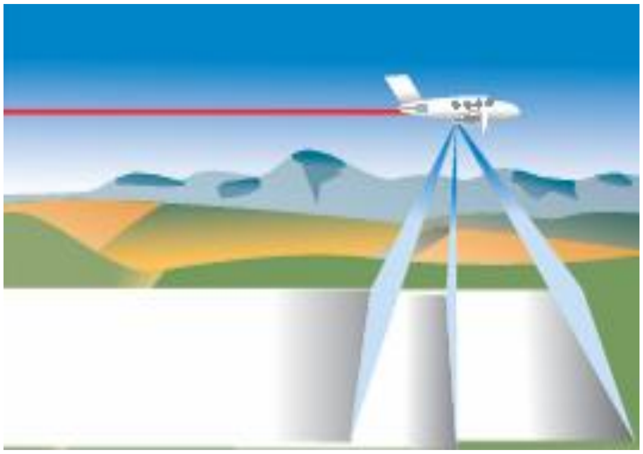

Figure 16. Push-broom sensors obtain stereo views by collecting forward and backward views for automated DSM/DTM production, plus downward view for digital orthophotos.

Photogrammetry is rarely used today for the sole purpose of generating DEMs, DSMs, DTMs or contours. However, airborne imagery is routinely acquired with forward overlap of 60% or more for production of digital orthophotos nationwide; this normally requires some form of aerial triangulation (AT). The 60% overlap creates stereo images required for all forms of photogrammetry (Figure 17), including manual photogrammetry (Figure 18) and automated photogrammetry (Figure 19) that can be used to produce DEMs. Without acquisition of any new imagery, existing imagery and AT solutions from orthophoto programs also can be used for DEM production. DEM accuracy (between 2.5 and 15 foot equivalent contour accuracy) depends on the flying height and rigor of the AT processes used.

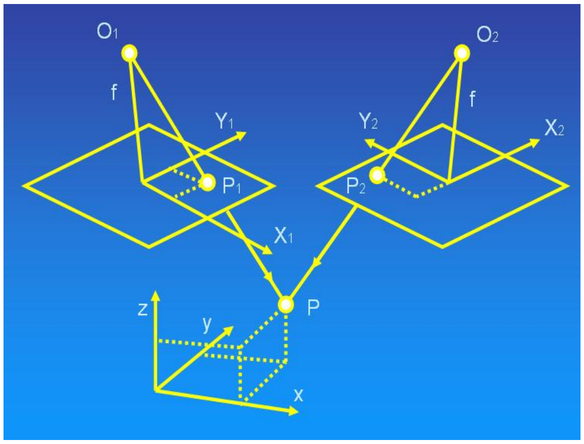

Figure 17. For any point to be mapped photogrammetrically, it must be visible on stereo images, both images seeing the same point P from two different perspectives (at P_1 and P_2). In this Figure, O_1 and O_2 are the locations of the camera's focal point when the two images were taken. Because trees normally block stereo views, it is difficult to map the bare earth terrain in vegetated areas using photogrammetry.

Figure 18. With manual photogrammetry, the compiler uses polarized glasses to see the left image with the left eye and the right image with the right eye, manually compiling spot heights where the bare earth terrain is visible in stereo and/or compiling 3D breaklines. Manually compiled contours are considered too expensive and time-consuming.

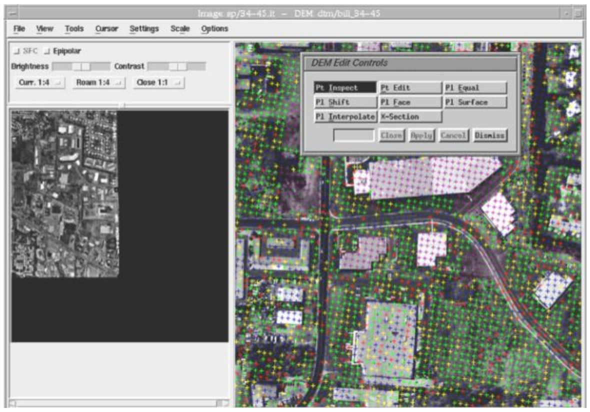

Figure 19. With automated photogrammetry, the computer correlates image pixels on stereo images and computes uniformly-spaced grid points that are initially DSM points of the top reflective surface. Semi-automated processes are then used to reclassify non-ground points so as to retain only the bare-earth DTM grid points (shown in green).

Table 1 summarizes the DEM accuracy achievable from imagery already acquired for production of digital orthophotos at various pixel resolutions, including 1-meter images for the National Agriculture Imagery Program (NAIP). Imagery and AT data would need to be preserved for re-use.

Table 1. How existing stereo imagery can be re-used to produce DEMs

Current Owner of Existing Imagery/AT	Orthophoto Pixel Resolution	Typical Flying Height above Terrain	Equivalent Contour Accuracy Achievable	Typical Vertical RMSEz
USGS/state/local	6-inch	4,800 feet	2.5 foot	23.2 cm
USGS/state/local	1-foot	9,600 feet	5 foot	46.3 cm
USDA (NAIP)	1-meter	30,000 feet	15 foot	1.39 meter

Interferometric Synthetic Aperture Radar (IFSAR)

Airborne IFSAR is acquired from approximately 35,000 feet above mean terrain, covering very large areas. X-band IFSAR, which maps the top reflective surface, is primarily used in the U.S. because other bands often interfere with communications and require special permissions for acquisition. Figure 20 shows an IFSAR DSM and Figure 21 shows an IFSAR DTM. Figure 22 shows the ortho-rectified radar image (ORI) of the same area; ORIs create *masks* of water areas that assist with hydrographic feature extraction and interpretation of data when producing hydro-enforced DTMs. Figure 23 shows the side-looking geometry used with IFSAR data collection; this geometry sometimes causes data voids caused by overlay, shadow and foreshortening, explained in the IFSAR chapter of the 2nd edition of "Digital Elevation Model Technologies and Applications: The DEM Users Manual," published by ASPRS; closer flight line spacing and different look angles are used to minimize this problem in mountainous terrain. Although not in the public domain, existing airborne IFSAR is currently available and licensed for all states except Alaska.

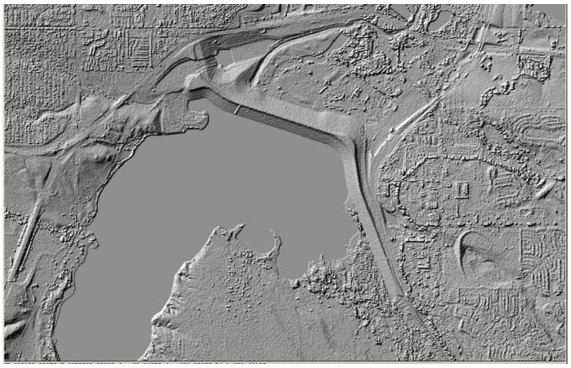

Figure 20. IFSAR collects the top reflective surface used to produce a digital surface model (DSM)

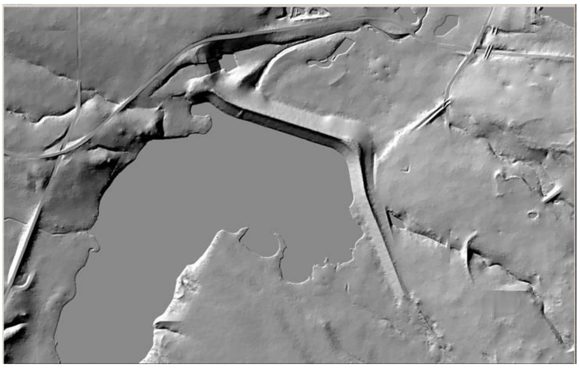

Figure 21. The IFSAR DSM is subsequently filtered to produce a digital terrain model (DTM)

Figure 22. IFSAR ortho-rectified radar image (ORI) used to generate water masks, eliminating need for breaklines

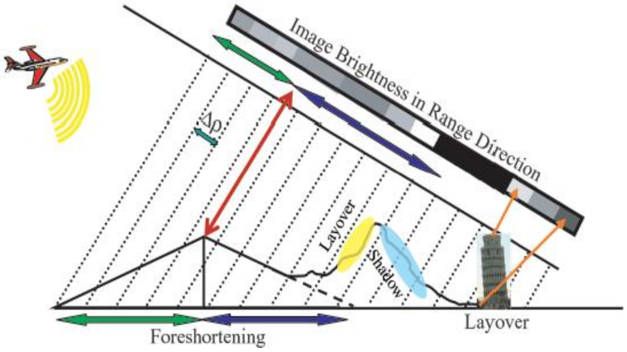

Figure 23. IFSAR maps to the side of the aircraft using principles of interferometry, but can create data voids from foreshortening, layover and shadow

Light Detection and Ranging (LiDAR)

LiDAR uses up to 200,000 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. DEM accuracies are routinely equivalent to 2-foot contour accuracy with standard LiDAR and approximately 1-foot contour accuracy with higher density/higher accuracy LiDAR. Figure 24 shows how it takes only a single LiDAR pulse to penetrate vegetation. Figures 25 and 26 show advantages of flying with 50% sidelap between adjacent flight lines and flying from lower altitudes. Figures 27 and 28 show how LiDAR maps through dense vegetation that normally could not be mapped by other technologies.

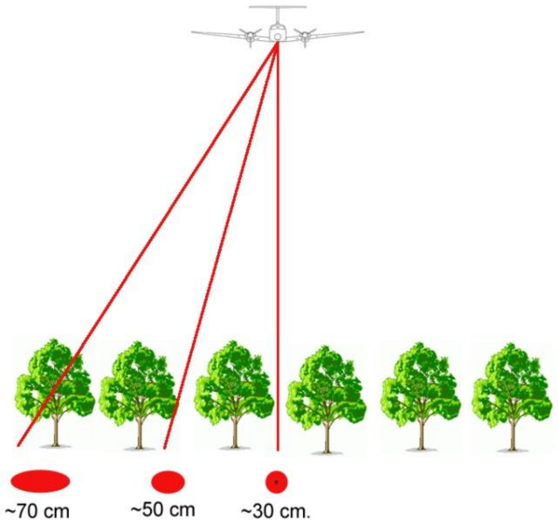

Figure 24. LiDAR can map the bare-earth terrain in forests by single pulses that penetrate *between* trees and even *through* trees in some instances. The footprint size of each laser pulse varies by the angle of the scan, as shown here. Normally acquired in zig-zag patterns, LiDAR scans are so dense 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.

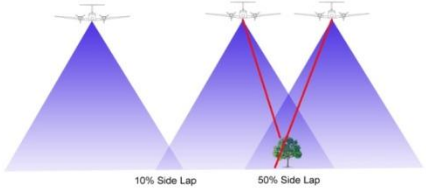

Figure 25. Flying with 50% sidelap between adjoining flight lines doubles the point density, increases the probability of penetrating dense vegetation by having two look directions from different perspectives, and provides alternative elevation points when a single swath includes high intensity returns that cause "trenching" and need to be eliminated from the dataset.

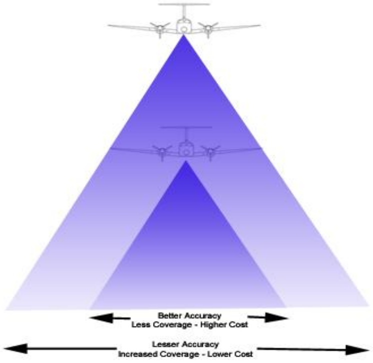

Figure 26. Vertical accuracy decreases with increased flying height, but costs can be reduced by flying form higher altitudes with higher point density.

Figure 27. 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.

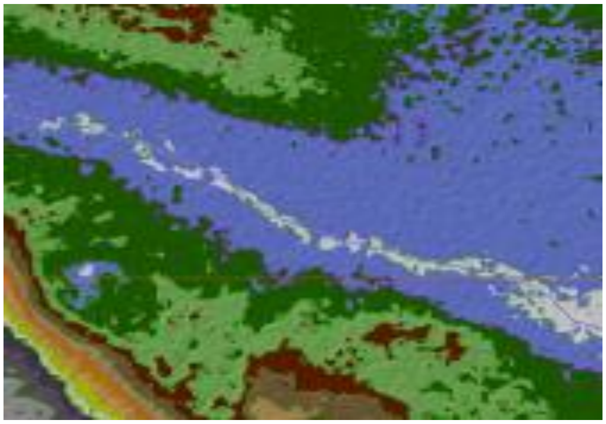

Figure 28. Color-coded by 1-foot contour elevation bands, the white polygons define depression contours that show dry *puddles* that should not normally be hydro-enforced (defined below).

LiDAR raw point cloud data are normally classified in the standard LAS file format using class 1 (processed, but unclassified), class 2 (bare-earth ground), class 7 (noise) and class 9 (water). Other LAS classes are used but beyond the scope of this questionnaire.

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. Figures 29 and 30 show examples of intensity images that include teaching points.

Figure 29. Intensity image showing streaks over water from multiple flight lines. This is not a problem because LiDAR measurements on water are already assumed to be unreliable and are classified separately as LAS Class 9. This entire image is usable for lidargrammetry.

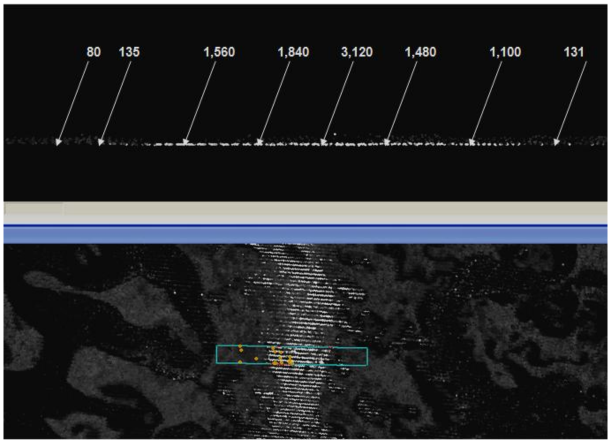

Figure 30. High intensity streaks over land and marshy areas can be problematic because high intensity returns cause "trenches" where elevations are mapped lower than their true elevation. The top image maps the different intensity values along the cross-section shown in the lower image.

LiDAR point cloud data is processed to ASPRS LAS 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 elevations in water are unreliable because sometimes the laser pulses are absorbed by the water, reflected from the water with differing intensities as shown above, or provide elevations on or below the level of the water surface. Most LiDAR data is 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.

It is normal for LiDAR elevation posts to appear to be noisy. However, in misguided attempts to smooth the terrain surface, analyses sometimes over-smooth and remove steep slopes that actually exist. Figure 31 is an example of over-smoothing, as demonstrated by a man-made channel that was constructed with the same cross-section dimensions throughout its length. The area on the left appears noisy, but the cross-section profile accurately shows the drainage channel to be about 50 feet wide with steeper slopes. The area on the right is seen to be smoother and more aesthetically pleasing; however, the cross-section profile incorrectly shows the drainage channel to be about 150 feet wide with shallower banks. For some applications, users prefer smoother terrain, but for hydraulic modeling and other applications, users need to know actual cross-section dimensions. It is normal for QA/QC reviews to test for over-aggressive smoothing.

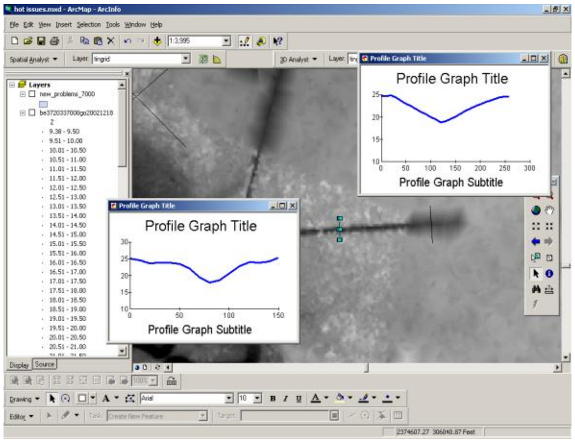

Figure 31. Although it appears noisy, the area on the left preserved the true shape of the man-made drainage channel, whereas the smoothed area on the right over-smoothed the shape of the same drainage channel, making it much wider and shallower.

All Technologies

The most important thing to remember about DEM production is that DEMs are interpolated from source data of higher density than the uniform post spacing of the DEM being produced. For example:

- DEMs with 1-meter (or 1/27-arc-second) post spacing are produced from elevation data with nominal pulse spacing (NPS) typically between 0.35 and 0.7 meters.
- DEMs with 3-meter (or 1/9-arc-second) post spacing are produced from elevation data with NPS typically between 1.0 and 2.0 meters. This is consistent with *USGS LiDAR Guidelines and Base Specifications*, v13.

FAQ #6: What is a LiDAR 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 32 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 DTM. First returns are used to produce the DSM.

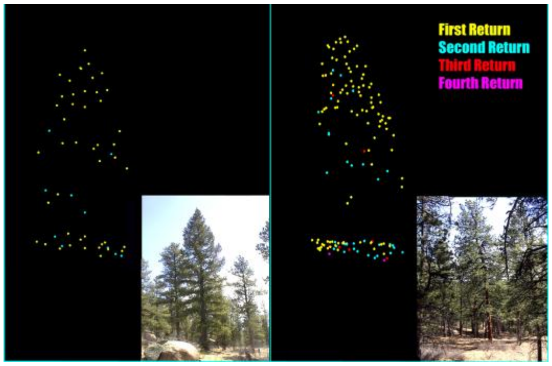

Figure 32. Examples of LiDAR point clouds

FAQ #7: What is a LiDAR cross-section?

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 33 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.

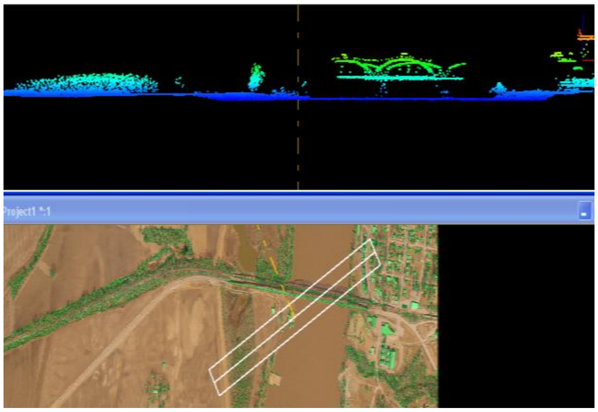

Figure 33. Digital orthophoto (lower image) shown with location of cross-section cut in LiDAR data. The upper image shows the elevations of all features along this cross-section.

FAQ #8: What is the difference between DEM post spacing and nominal pulse spacing (NPS)?

Within the NED, *DEM post spacing* is uniformly-spaced, but as a fraction of an arc-second (see Figure 7, above). *DEM post spacing* outside the Federal government is normally uniformly-spaced, usually as some whole integer value of meters, e.g., 1, 2, 5 or 10 meters (see Figure 8, above).

Nominal pulse spacing (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; standard procedures are under development by ASPRS for NPS calculations.

Figure 34 shows high density NPS in red (left) and low density interpolated DEM *posts* (right).

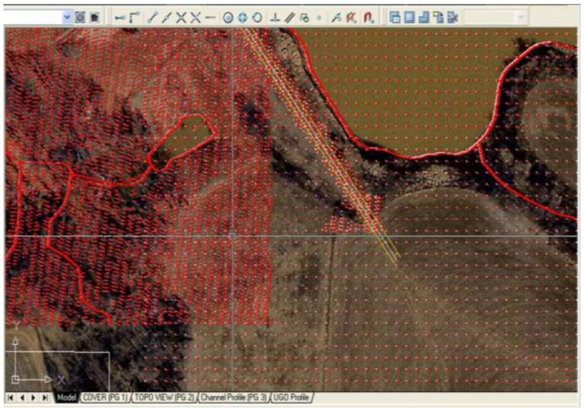

Figure 34. Higher density, irregularly-spaced LiDAR mass points (red) are used to interpolate the lower density DEM grid points shown on the right. Several hydro breaklines are also shown in this image.

For USGS acceptance, the spatial distribution of geometrically usable points is expected to be uniform and free from clustering. In order to ensure uniform densities throughout the data set, a regular grid, with cell size equal to the design NPS x 2 is laid over the data. At least 90% of the cells in the grid must contain at least 1 LiDAR point. NPS assessment is made against single swath, first return data located within the geometrically usable center portion (typically ~90%) of each swath. Average along-track and cross-track point spacing should be comparable. Point density and NPS comparisons are shown here.

Point Density	NPS
8 pt/m^2	0.354 m
6 pt/m^2	0.408 m
4 pt/m^2	0.500 m
2 pt/m^2	0.707 m
1 pt/m^2	1.0 m
0.25 pt/m^2	2.0 m
0.04 pt/m^2	5.0 m

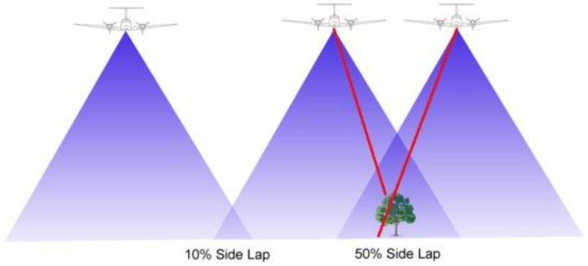

Figure 35. Comparison between 10% and 50% side lap between overlapping LiDAR swaths

Instead of flying with a minimal side lap of 10%, many firms now acquire their LiDAR data with 50% side lap, as shown at Figure 35. This minimizes the risk of having gaps in data between flight lines caused by excessive roll and pitch of the aircraft during windy conditions; and this increases the probability of penetrating dense vegetation by having two different look angles, as also shown at Figure 35. A side lap of 50% doubles the average point density compared with single swaths.

FAQ #9: What is the difference between RMSEz, equivalent contour accuracy, and other terms used to describe vertical accuracy?

For decades, contour lines were developed for human interpretation of elevations on printed topographic maps, and the contour interval defined the map's vertical accuracy. The contour interval had a specific meaning for satisfaction of the National Map Accuracy Standard (NMAS), i.e., not more than 10 percent of the elevations tested may be in error more than one-half the contour interval. In other words, 90 percent or more of errors should be equal to or less than one-half the contour interval.

Contour lines can be produced today from DEMs and digital elevation data with virtually any contour interval, but this would be misleading if it falsified the vertical accuracy of the elevation data from which the contours were derived. In 1998, the Federal Geographic Data Committee published the National Standard for Spatial Data Accuracy (NSSDA) which implemented a statistical and testing methodology for estimating the positional accuracy of points on maps and in digital geospatial data, with respect to georeferenced ground positions of higher accuracy. The NSSDA specified that vertical accuracy be specified in statistical terms at the 95% confidence level, defined as 1.9600 x RMSEz when errors follow a normal error distribution. In 2004, recognizing that LiDAR DTM errors do not necessarily follow a normal error distribution, the National Digital Elevation Program (NDEP) published its "Guidelines for Digital Elevation Data" and the American Society for Photogrammetry and Remote Sensing (ASPRS) published the "ASPRS Guidelines, Vertical Accuracy Reporting for Lidar Data." The NDEP and ASPRS guidelines both distinguished between Fundamental Vertical Accuracy (FVA) in open, non-vegetated terrain, and Supplemental Vertical Accuracy (SVA) in individual land cover categories and Consolidated Vertical Accuracy (CVA) in combined land cover categories. It is now common for LiDAR specifications to require a higher vertical accuracy in open terrain (FVA) and a lower vertical accuracy in vegetated terrain (for the SVA and CVA). Both the SVA and CVA allow the use of 95th percentile errors rather than errors computed statistically at the 95% confidence level. Both the 95% confidence level and the 95th percentile define vertical accuracy in terms of the vertical linear uncertainty such that the true or theoretical location of the point falls within ± of that linear uncertainty value 95-percent of the time.

Consistent with NSSDA, NDEP and ASPRS guidelines, Table 2 compares the vertical $RMSE_z$ and vertical accuracy at the 95% confidence level necessary for digital elevation data to have the equivalent contour accuracy specified in the left column. Because most users are still confused by an RMSEz of 18.5 cm, for example, or vertical accuracy of 36.3 cm at the 95% confidence level, the geospatial community translates these terms into 2-ft equivalent contour accuracy, as demonstrated in Table 2 and for a range of other common contour intervals. It must also be noted that contours, used for human visualization, are in decreasing demand because of hillshades and other forms of 3-D visualization from digital elevation data. Today, most terrain analyses are performed by computer analyses of DEMs or other forms of digital elevation data for which contour lines, themselves, are meaningless.

Table 2. Equivalent Contour Accuracy for Common Statistical Accuracy Terms.

Equivalent Contour Accuracy	$RMSE_z$	NMAS Vertical Accuracy at 90% Confidence Level	NSSDA Vertical Accuracy at 95% Confidence Level
1-foot	9.25 cm (~0.3 ft)	0.5 ft	18.15 cm (~0.6 ft)
2-foot	18.5 cm (~0.6 ft)	1.0 ft	36.3 cm (~1.2 ft)
5-foot	46.3 cm (~1.5 ft)	2.5 ft	90.8 cm (~3.0 ft)
10-foot	~3 ft	5.0 ft	~6.0 ft
15-foot	~4.5 ft	7.5 ft	~9.0 ft
20 foot	~6 ft	10.0 ft	~12.0 ft

FAQ #10: How do I determine what DEM post spacing or nominal pulse spacing (NPS) I need?

The determination of the minimal acceptable point density, DEM post spacing and/or NPS needed to satisfy Business Uses is central to the purpose of this questionnaire. Respondents should not 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. The current DEM resolutions in the NED can be used for comparison purposes. It is easier to see the visual effects of resolution than the visual effects of elevation accuracy. Figure 36 shows a digital orthophoto of the Pecatonica River, in Winnebago, County, IL. The National Elevation Dataset (NED) uses arc-second DEM post spacing, typically 1-arc-second (~30 meter spacing at the Equator, see Figure 37), 1/3-arc-second spacing (~10 meter spacing at the Equator, see Figure 38), and 1/9-arc-second spacing (~3 meter spacing at the Equator, see Figure 39). All three resolutions shown have the same vertical accuracy, though their horizontal resolutions are very different.

Figure 36. Digital Orthophoto, Winnebago County, IL

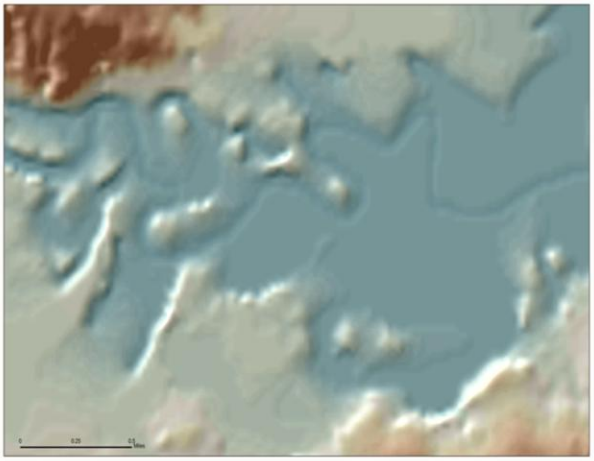

Figure 37. DEM, 1-arc-sec (~30 meter post spacing)

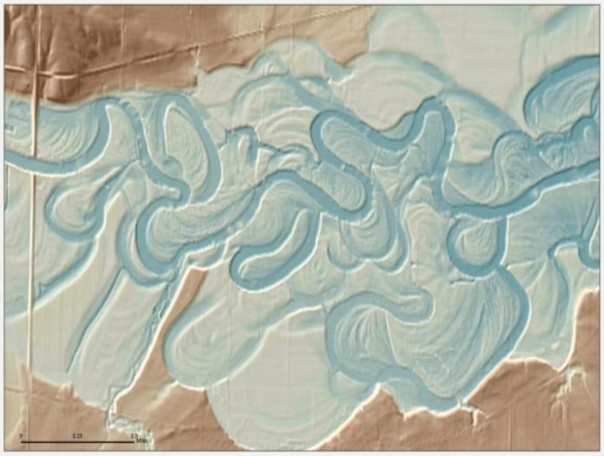

Figure 38. DEM, 1/3-arc-sec (~10 meter post spacing)

Figure 39. DEM, 1/9-arc-sec (~3 meter post spacing)

- If you can *see* what you need from the 1-arc-second (~30 meter) DEM at Figure 37, and if your Business Use can accept DEMs produced for the NED from topographic quad maps that are about 50 years old, the status quo may be acceptable. Then you probably have no Business Use requirement for enhanced elevation data unless you also need DSMs.
- If you can *see* what you need from the 1/3-arc-second (~10 meter) DEM at Figure 38, your Business Use DEM needs may be satisfied by 10-meter NED data where it already exists, produced from old topographic quad map source data. Elsewhere, you may need elevation data (DSMs/DTMs) produced from IFSAR (Quality Level 4) or elevation data produced photogrammetrically from existing imagery (Quality Level 3).
- If you can *see* what you need from the 1/9-arc-second (~3 meter) DEM at Figure 39, but cannot see what you need from the 1-arc-second or 1/9-arc-second DEM from the NED, your Business Use probably needs elevation data produced from standard LiDAR (Quality Level 2).
- USGS is now considering 1/27-arc-second DEM post spacing (~1 meter post spacing at the Equator) as appropriate for gridded DEMs from LiDAR acquired with sub-meter NPS (Quality Level 1). This Quality Level requires alternative consideration because it is difficult to visually see the difference between a DEM with 3-meter, 2-meter and 1-meter post spacing.

- 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 40 and 41.

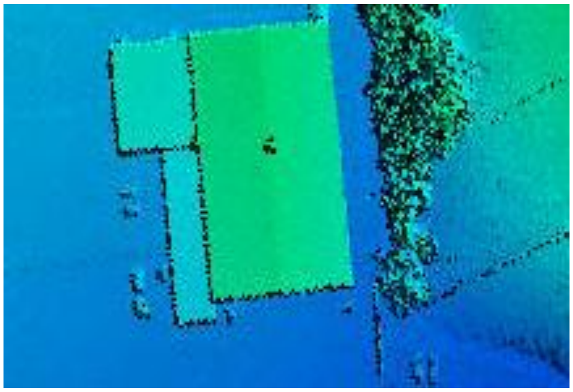

Figure 40. Even with sub-meter NPS, building footprint edges are pixilated. Straight edges are difficult to define when they are irregular and pixilated.

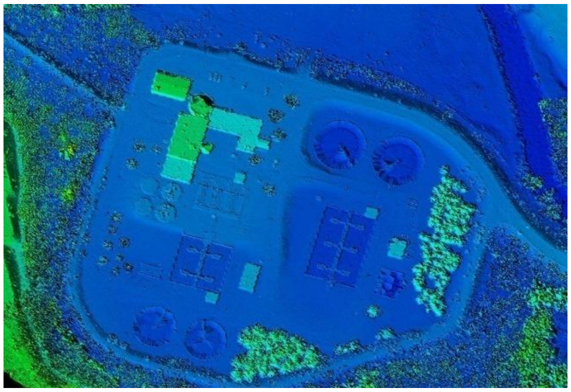

Figure 41. High resolution elevation data are required when LiDAR is used for semi-automated feature extraction. Many misclassifications result from low resolution elevation data.

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Consideration #3 (What you need to measure). Your DEM user application has everything to do with required point density. Table 3, 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 21 and 22 (see FAQ #5) show an example of LiDAR data in Florida where LiDAR data was collected with an average density of 4 points/m^2 in dense tropical vegetation. This worked in Florida, but in the Pacific Northwest, 4 points/m^2 may not be good enough for specific applications.

A paper entitled, "Minimum LiDAR Data Density Considerations for the Pacific Northwest," by Watershed Sciences, Inc, 01/22/10, stated the following: "Not all pulses emitted from the laser will measure the ground. Depending on vegetation and land cover, few pulses, and in some cases, no laser pulses, will reach the ground. In order to relate pulse density to ground point density, a mathematical relationship has been calculated from public-domain LiDAR surveys collected in Oregon in the last two years. For these surveys, totaling over 5.2 million acres, a resolution of 8 pulses per square meter was achieved. It was found that for any one pulse emitted, the probability of being classified as ground was only 14%." Analyses were performed to recommend pulses per square meter and NPS for different applications used in the Pacific Northwest, as summarized in Table 3.

Table 3 addresses both considerations #3 and #4.

Table 3. Watershed Sciences, Inc's Recommended Resolution for LiDAR Applications in the Pacific Northwest

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

The prior answers to FAQ #5 and FAQ #8 both 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. In this case, 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.

<u>Consideration #5 (Breakline needs)</u>. A decade ago, breaklines were initially required by FEMA when DEM post spacing was 5 meters; however, FEMA now specifies breaklines as optional, especially because DEM post spacing is now at the 1-meter level. <u>The denser the nominal pulse spacing (NPS), the less the requirement for expensive breaklines that often double the cost of a LiDAR project</u>.

For nearly a century, evolving technologies have enabled the mapping community to automate production and speed delivery of geospatial data to users at vastly reduced costs. Orthophotos are often updated annually because they can be quickly and efficiently produced. The same is mostly true for LiDAR point cloud data, but not for breaklines. In fact, there is a disturbing trend to require extensive breaklines that are labor intensive (often sent to China or India for production), costly and time-consuming to produce, and perhaps are not really needed.

Figure 42 shows typical LiDAR mass points with NPS of approximately 1 meter. For most automated processes, these elevation points adequately model the terrain. Figure 43 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 42 is acceptable, or if the "Cadillac version" at Figure 43 warrants the significant cost increases 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 42. LiDAR mass points with nominal pulse spacing (NPS) of approximately 1 meter

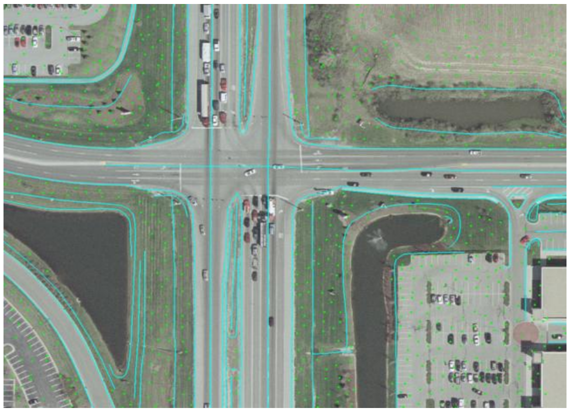


Figure 43. Thinned model key points and breaklines for swales, borrow pits with water, and road features

FAQ #11: What is the difference between hydro-flattening and hydro-enforcement?

Hydro-flattening is a relatively new term used by USGS to explain how DEMs are traditionally processed for inclusion in the NED. 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.

Figures 44 and 45 demonstrate how the shoreline elevations of lakes and reservoirs are flattened.

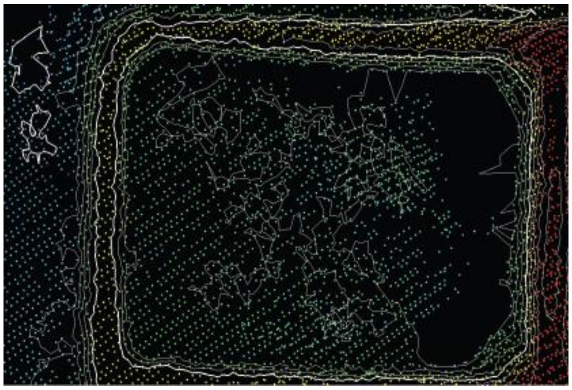


Figure 44. LiDAR mass points in this nearly-dry reservoir have variable elevations. It is difficult to identify the water shoreline or its flat elevation.

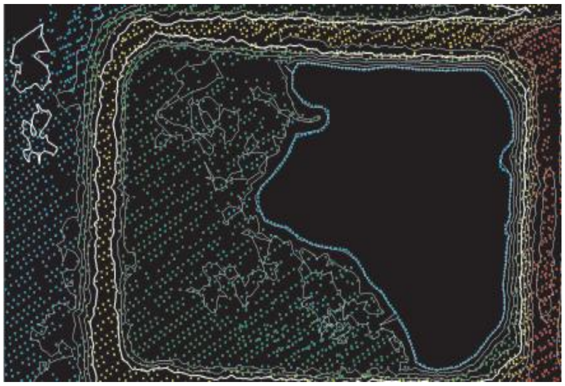
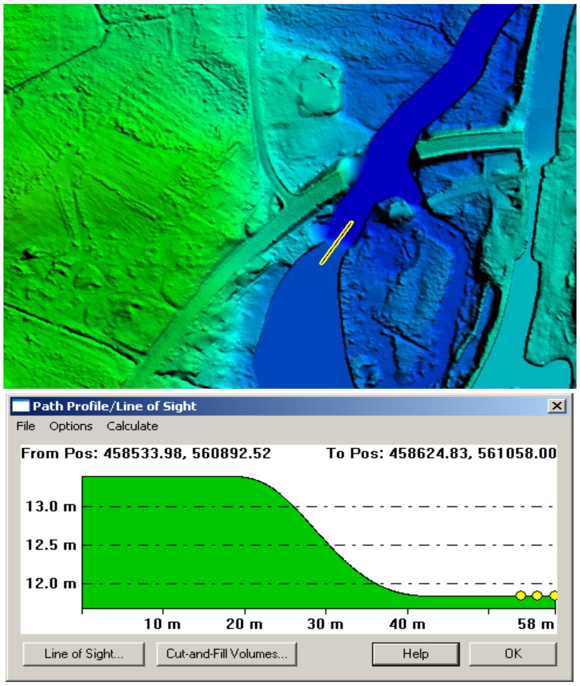


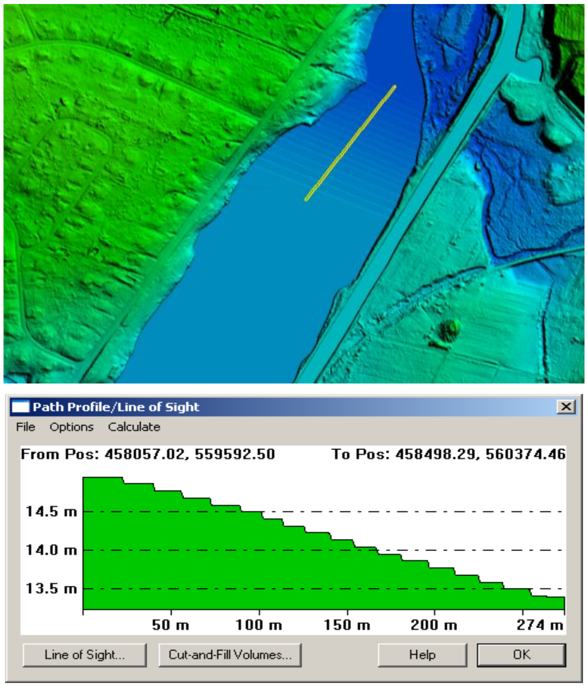
Figure 45. Special software is used to generate the breakline for the shoreline used to flatten the water surface elevation for this reservoir.

Figures 46 and 47 demonstrate how dual-line drainage features ≥ 100 feet in width are flattened from shore to shore. Per *USGS LiDAR Guidelines and Base Specifications*, v13, these streams do not necessarily have monotonic gradients that decrease as the river flows downstream, though this is normally done anyhow in a process call hydro-enforcement. Gradients can be smooth (Figure 46) or stair-stepped (Figure 47) so long as the height of the steps are not too steep and each step is flat from shore to shore on either side of the river. Narrower rivers are depicted as single-line drainage features that do not require flattening but may require hydro-enforcement.



From Pos: 458533.98, 560892.52 To Pos: 458624.83, 561058.00

Figure 46. Hydro flattened dual-line stream (top) with a smooth gradient (bottom). Top image also shows bridge removed from the DEM.



From Pos: 458057.02, 559592.50 To Pos: 458498.29, 560374.46

Figure 47. Hydro flattened dual-line stream (top) with a stair-stepped gradient (bottom). Each stair step in this example is 10 cm high (– 4 inches).

Figures 48 and 49 demonstrate how all bridges over such rivers, recognized as man-made features constructed above the bare earth terrain, are removed from the DEM; but with hydro-flattening, below-ground culverts are not "cut" to allow water to pass under the road.

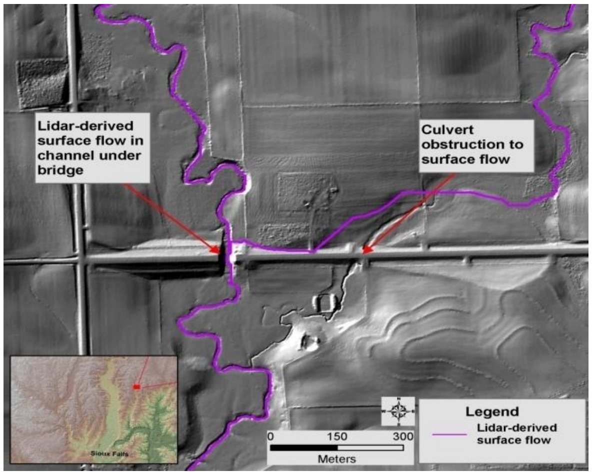


Figure 48. Elevations on the bridge are removed to allow mapping and flattening of the river beneath the bridge. The underground culvert is not cut, artificially diverting the flow along the north side of the road until reaching the river.

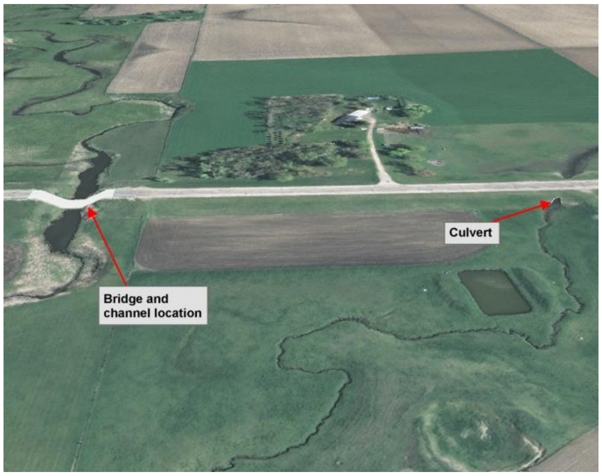


Figure 49. This shows an oblique view of a digital image draped over the hydro-flattened DEM from the prior Figure. The bridge deck is lowered to the elevation of the ground beneath. The culvert on the right is clearly visible.

<u>*Hydro-enforcement*</u> includes hydro-flattening, as defined by USGS, but includes additional steps for treatment of dual-line and single-line streams to enforce the downward flow of water. Figures 50 and 51 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 50 but enforces the downward flow of water in the hydro-enforced TIN at Figure 51.

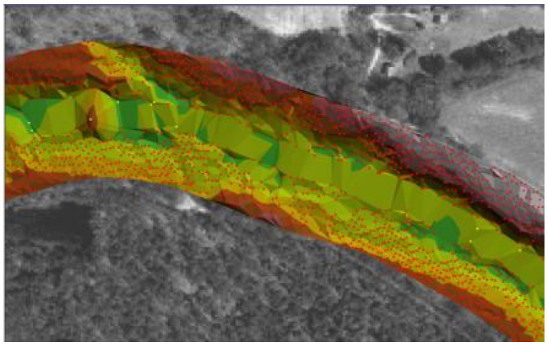


Figure 50. Rocks in the river, and/or natural undulating elevations along the shorelines, make the TIN appear as though water cannot pass downstream.

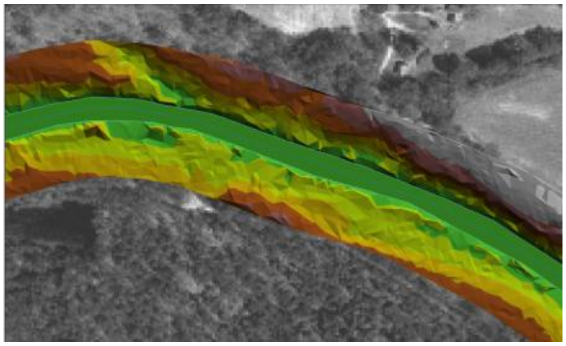
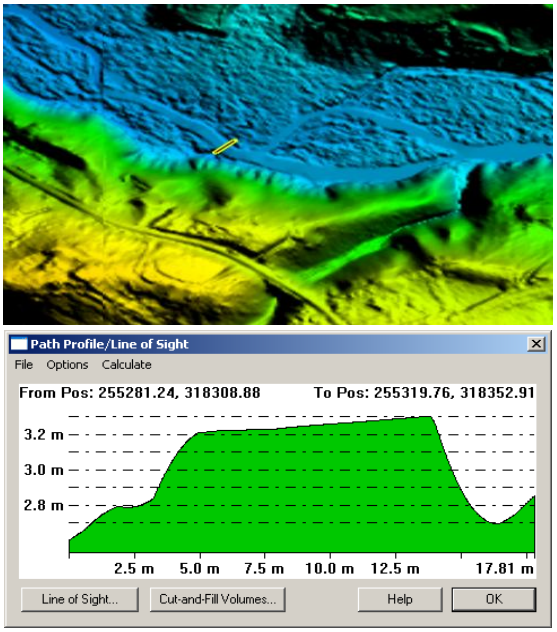


Figure 51. Breaklines for the dual shorelines are cut beneath the mapped elevations in order to hydro-enforce the flow of water; but this can create other problems.

If the dual shorelines are cut too deep the shoreline appears to have steep cliffs that are unrealistic; but if the dual shorelines are not cut deep enough the elevation of the water surface for the flattened river is depicted as higher than the surrounding terrain elevations as shown at Figure 52 – clearly unacceptable.

In this latter example, as is common, it was assumed that the elevations along the shoreline decreased uniformly from known elevations upstream and known elevations downstream; but the gradient was actually irregular. Both upstream and downstream of the cross-section shown, the river's water surface elevation is correctly enforced below the surrounding terrain; but in the middle, the water surface was incorrectly enforced *higher* than the surrounding terrain elevations.



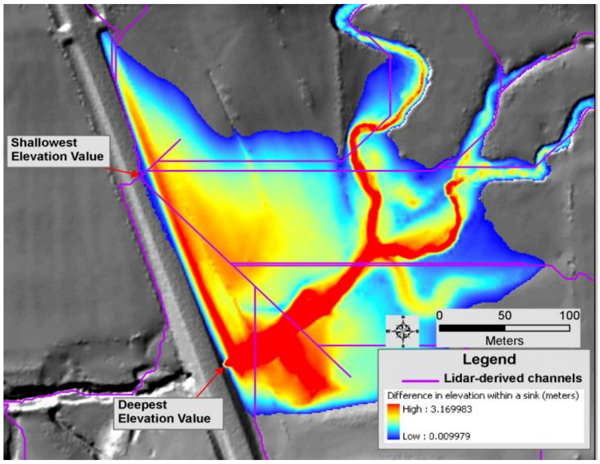
From Pos: 255281.24, 318308.88

To Pos: 255319.76, 318352.91

Figure 52. Water surface elevation incorrectly hydro-enforced higher than surrounding terrain.

Both hydro-flattening and hydro-enforcement address this issue for dual-line streams, but hydro-flattening does not mandate hydro-enforcement.

There are no uniform standards for hydro-enforcement of below-ground culverts. Even FEMA now leaves it up to the hydraulic engineer to determine when, where and how to hydro-enforce streams, bridges and culverts of all sizes. Figure 53 shows what happens when a culvert is not hydro-enforced, and Figure 54 shows what happens when a culvert is hydro-enforced.



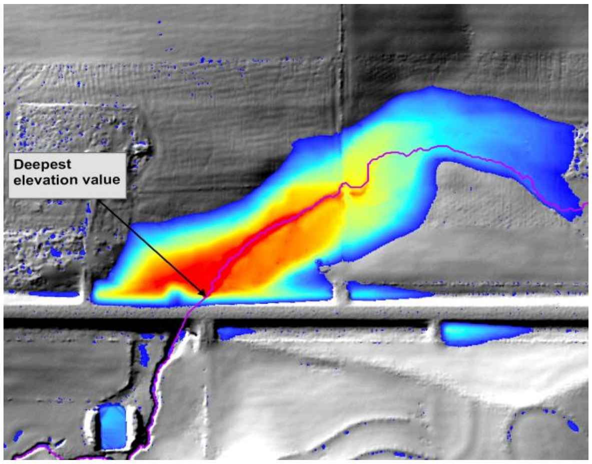


Figure 53. This shows what happens when the culvert is <u>not</u> hydro-enforced. The water flows in the ditch beside the road until it overflows the road at its shallowest elevation where the purple line crosses the road.

Figure 54. This shows the same culvert as in Figures 48 & 49, but now "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.

<u>Puddles</u> are one or more elevation posts totally surrounded by higher elevations. Figures 53 and 54 show puddles with red being the deepest part of the 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 54 with the purple connector line that crosses the road. Figure 28 (see FAQ #5) shows dry puddles that should not normally be drained; 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.

FAQ #12: What are 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 55 and 56. They normally use a color elevation ramp, but some hillshades are black and white.

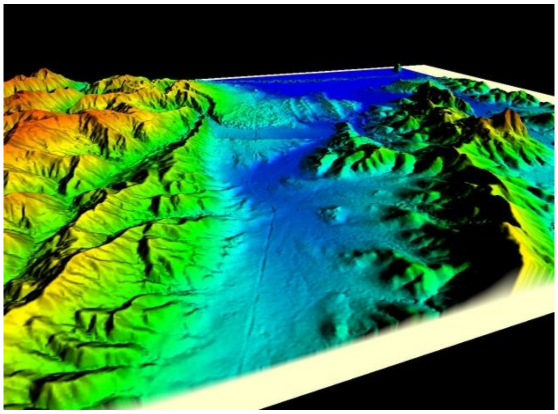


Figure 55. Hillshade with 45°sun angle and 45° azimuth.

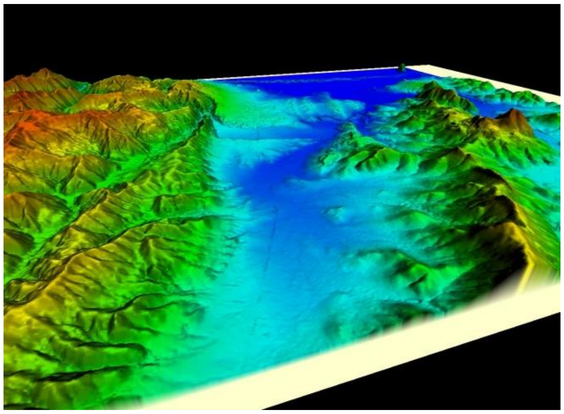


Figure 56. Hillshade with 70° sun angle and 70° azimuth.

Figure 57 shows how the B/W hillshade supplements the orthophoto in Figure 58.

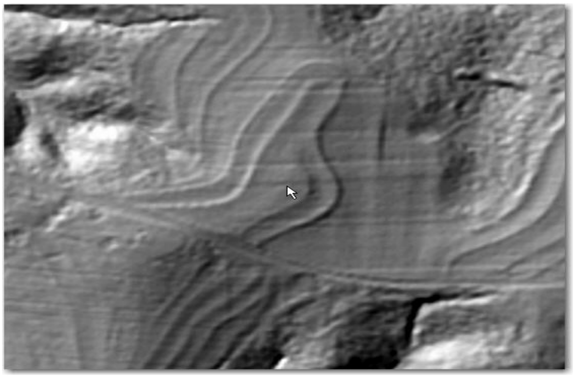


Figure 57. Hillshades in black and white are also effective in visualization of the 3D topographic surface.

Figure 58. This color orthophoto does not reveal the topographic characteristics clearly visible in the prior figure.

FAQ #13: What are elevation derivatives?

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

Figure 59 shows a simple hillshade of ridge lines and surrounding hills.

Figure 60 shows a slope map where red areas are the steepest and green areas are the flattest.

Figure 61 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.

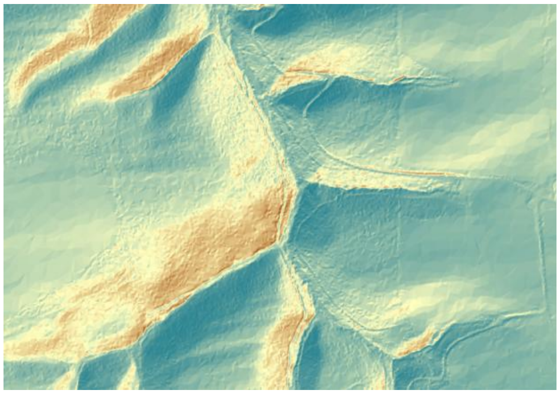


Figure 59. Hillshade of ridge and hills.

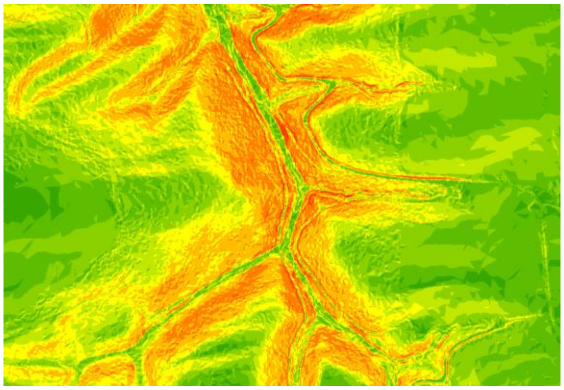


Figure 60. Color-coded slope map of ridge and hills.

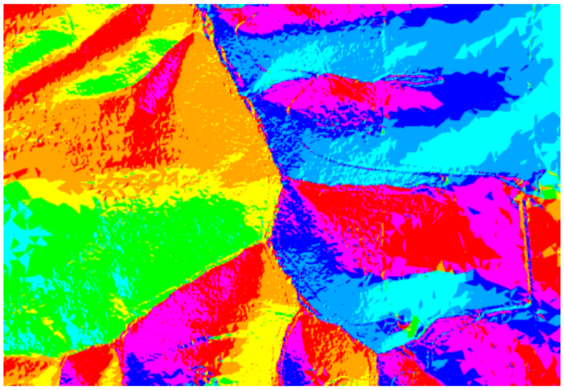


Figure 61. Color-coded aspect map of ridge and hills

As demonstrated in Figures 62 and 63, 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.

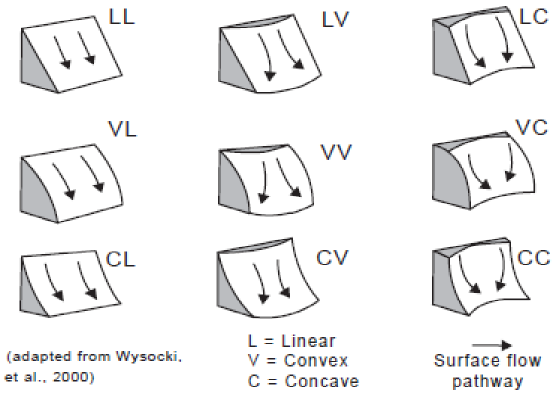


Figure 62. Curvature types.

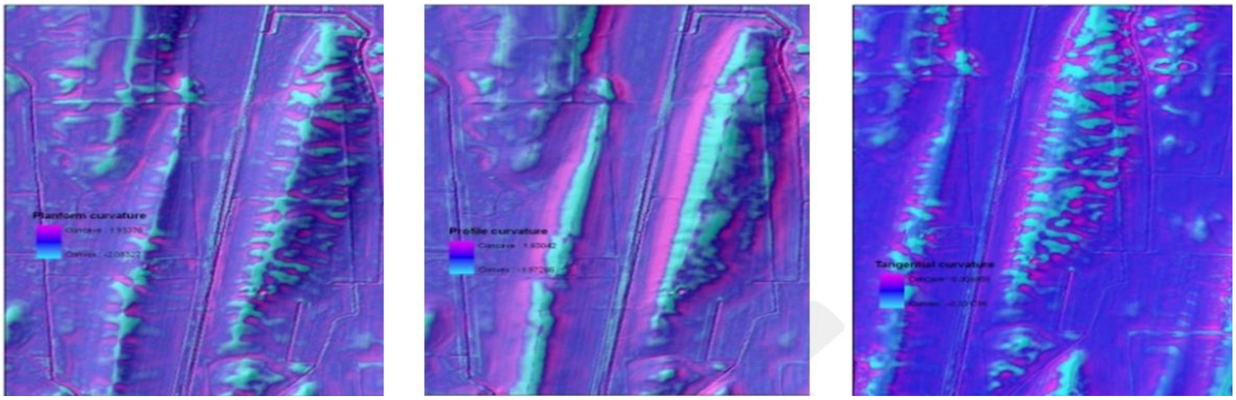


Figure 63. Plan form curvature (left); profile curvature (center); tangential curvature (right) generated from ESRI software.

FAQ #14: How frequently does elevation data need to be updated?

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

Factors that Affect Hydraulic Analyses by FEMA. Volume 1, *Flood Studies and Mapping*, of FEMA's "Guidelines and Specifications for Flood Hazard Mapping Partners" explains FEMA's procedures for performing Mapping Needs Assessment to evaluate whether the flood hazard data and other data shown on a Flood Insurance Rate Map (FIRM) are adequate. If the data on the FIRM are not adequate, the community will identify the specific data elements that need to be updated, e.g., flood hazard data for specific flooding sources, or base map information. The Mapping Needs Assessment forms the basis for selecting and prioritizing Flood Map Projects to be initiated. 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); 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.

In the section entitled Minimum Standards for Community-Supplied Data, which includes elevation data and digital orthophotos, the Currency paragraph states: "The data must have been created or reviewed for update needs within the last 7 years." This document was interpreted by the National Research Council (NRC) to mean that "FEMA floodplain mapping standards require elevation data preferably measured during the last seven years." In two reports entitled "Elevation Data for Floodplain Mapping" (NRC, 2007) and "Mapping the Zone: Improving Flood Map Accuracy" (NRC, 2009), the NRC strongly recommended that FEMA collaborate with other user agencies to improve both the accuracy and currency of elevation data used for flood hazard mapping; and FEMA has taken positive steps to implement these NRC recommendations.

<u>Subsidence Monitoring</u>. Digital elevation data are used to monitor land subsidence, the loss of surface elevation due to removal of subsurface support. Subsidence occurs in nearly every state in the U.S. 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 64 demonstrates the magnitude of the problem in California. The sign near the top of the electric pole shows the position of the land surface in 1925; the sign in the middle of the pole shows the elevation in 1955; and the sign on the ground shows the elevation of the ground in 1977 when this photo was taken. Subsidence has continued to the present time, and the valley has subsided for miles in all directions.

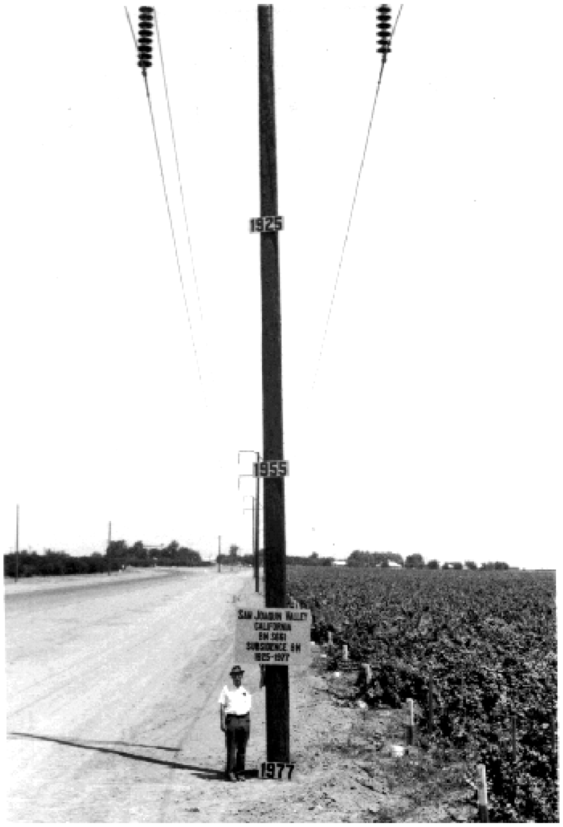


Figure 64. Fifty years of subsidence in California's San Joaquin Valley. Image courtesy of National Geodetic Survey (NGS).

During a five year period of drought, the California Department of Water Resources estimated the state's aquifers were being over-drafted at the rate of 10 million acre-feet per year. Unfortunately, the results of over-drafting of aquifers has led to many problems caused by land subsidence, including:

- 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

The National Research Council (NRC, 1991) conservatively estimated the annual subsidence costs due to increased flooding and structural damage to be in excess of $125 million. These estimates do not include loss of property value due to condemnation, and they do not consider increased farm operating costs (re-grading of land, replacement of pipelines, replacement of damaged wells) in subsiding areas. The NRC estimates annual subsidence costs may be about $400 million nationally, including over $180 million per year for the San Joaquin Valley, California, over $30 million per year for Santa Clara County, California, over $30 million per year for the Houston-Galveston, Texas area, $30 million per year for New Orleans, Louisiana, and $10 million per year for the State of Florida. The Louisiana coast line is undergoing constant coastal change, and it is subsiding at an alarming rate — as much as 1.5" per year is some areas. Combined with the predicted sea level rise of 1" every 30 months, millions of people now living in south Louisiana will see this land area and population living at and below sea level by the end of the current century. The frequency with which LiDAR data needs to be reacquired for monitoring of subsidence is directly proportional to the annual rate of subsidence.

Analysis of Sea Level Rise. Nearly every coastal State has requirements to predict the future impacts of sea level rise, 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.

Sea level rise is a significant issue that threatens coastal environments and communities. According to a report of the Environmental Protection Agency, this rise could be as high as one meter during the next century. When the White House asked the EPA for statistics on the number of buildings to be impacted by the predicted sea level rise, EPA attempted to use DEMs from the NED, but found them to be unacceptable. The EPA lacked the DEMs accurate and current enough to perform this modeling effort. Without the appropriate elevation data, it is difficult to gather a good understanding of sea level rise impacts. This leads to problems for coastal zone managers and engineers needing to formulate strategies to mitigate the effects of a rise in sea level. The availability of accurate elevation data can help in understanding the possible effects of sea level rise on coastal morphology (erosion and deposition) and ecosystem habitats that have limited vertical and horizontal positions in the coastal environment, as shown at Figure 65.

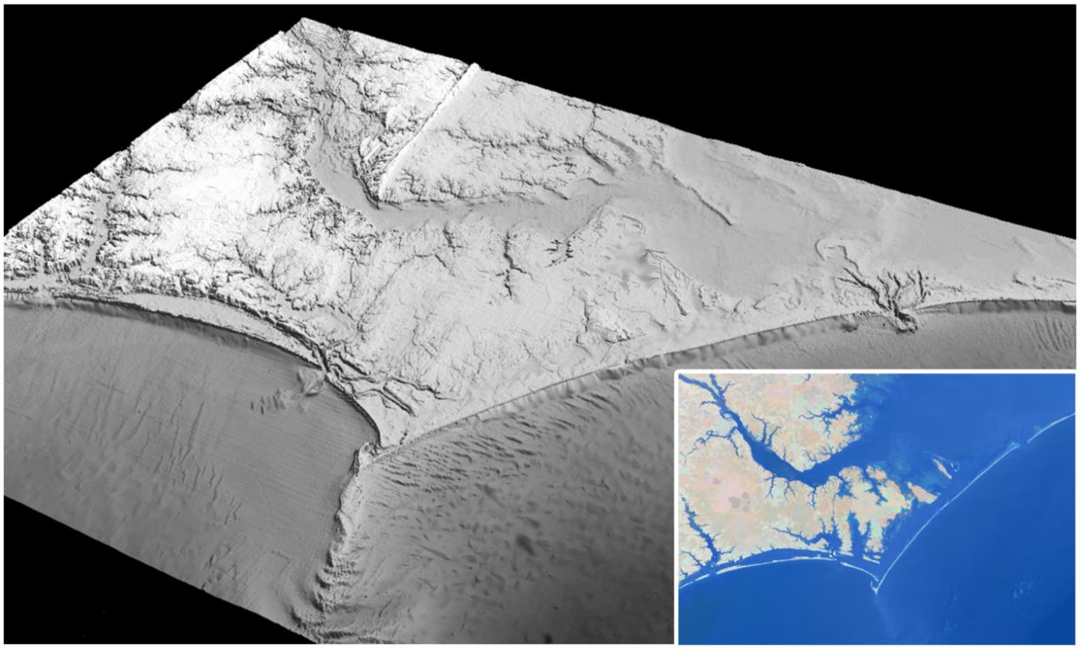


Figure 65. A seamless topographic/bathymetric elevation model utilized to simulate sea level rise scenarios. The inset illustrates an approximate one meter sea level rise based on the topo/bathy DEM. Image courtesy of NOAA.

Researchers at NOAA are trying to understand the effects of sea level rise in coastal states, such as North Carolina. One of the first steps to understanding this process is to construct an accurate DEM. In the case of North Carolina, a seamless topo/bathy DEM was constructed utilizing the most accurate and current elevation data available. The DEM utilized FEMA LiDAR data for topographic information and NOAA hydrographic soundings for bathymetric information to produce a continuous bathy/topo DEM relative to NAVD 88. Since this DEM was constructed from varying elevation data sets, these various data sets needed to be referenced to a common vertical datum using NOAA's VDatum tool.

To assess the impacts of sea level rise, simulations can be developed by combining a finite element hydrodynamic model with the consistent, continuous elevation dataset. The scenarios can simulate tidal response, synoptic wind events, and hurricane storm surge propagation in combination with sea level rise. Accurate prediction of inundation patterns can be accomplished by merging the high resolution, continuous bathymetric/topographic data with an accurate wetting/drying algorithm. Shoreline migration can then be dynamically computed from the algorithm's output as a function of sea level rise, and coupled to characterize the effects of sea level rise on coastal ecosystems. The availability of accurate and current high resolution bathymetric and topographic datasets holds an enormous possibility for helping understand the impact of sea level rise to the coastal environment.

As vital input to this study, NOAA will be asked to provide their estimates of when existing elevation data are too obsolete to be used for credible assessments of the status and impacts of sea level rise.

<u>Monitoring of Post-Glacial Rebound</u>. Post-glacial rebound is the rise of land masses that were depressed by the huge weight of ice sheets during the last glacial period, through a process known as isostasy. The enormous weight of this ice caused the surface of the Earth's crust to deform and warp downward,

forcing the fluid mantle material to flow away from the loaded region. As glaciers now retreat, the removal of the weight from the depressed land leads to slow and ongoing uplift or rebound of the land and the return flow of mantle material back under the deglaciated area. Post-glacial rebound affects vertical and horizontal crustal motion, global sea levels, gravity fields, vertical datums, the Earth's rotational motion, state of stress and intraplate earthquakes, and recent global warming.

With receding glaciers in Alaska for example, post-glacial rebound is measured vertically in centimeters per year. Ground elevations are rising higher above sea level and boat docks at some traditional fishing villages are now dry or too shallow for fishing boats. This has minimal impacts inland and largely impacts coastal areas where periodic monitoring is required.

Management of Forests. LiDAR, IFSAR and stereo imagery can all be used to map the changing heights of trees on 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.

Soil Conservation. In 1935, during the peak of the "Dust Bowl," steep slopes were clear cut, dust storms were carrying soil from the nation's midsection to Washington, D.C. and Hugh Hammond Bennett was campaigning for Congressional action to stop erosion. Congress acted and passed the Soil Conservation Act in 1935, creating the Soil Conservation Service, now known as the Natural Resources Conservation Service (NRCS).

Hugh Hammond Bennett became the first Chief of the CSC, and he focused on management of slopes for reduction of soil erosion. His seminal book, entitled "Elements of Soil Conservation," had chapters with the following names, largely linking soil erosion to management of slopes: (1) The Erosion Problem in the Unites States, (2) Extent of Erosion, (3) Effects of Erosion, (4) How Erosion Takes Place, (5) Rates of Erosion and Runoff, (6) Climate and Soil Erosion, (7) Rainfall Penetration, (8) A National Program of Soil Conservation, (9) Planning for Conservation of Soil and Water, (10) Use of Vegetation in Soil and Water Conservation, (11) Contouring, (12) Terracing, (13) Channels and Outlets, (14) Gully Control, (15) Control of Erosion on Stream Banks, (16) Water Spreading, (17) Wildlife and Soil Conservation, (18) Farm Ponds for Water Storage, (19) Stubble-Mulch Farming, (20) Farm Drainage, (21) Farm Irrigation, (22) The Place of Trees and Shrubs in Soil and Water Conservation, and (23) Upstream Flood Control.

Two of Mr. Bennett's quotes remain NRCS mottos to this day:

- "Every additional gallon of water that can be stored in the soil through the use of conservation measures means one gallon less contributed to flood flows."
- "Take care of the land and the land will take care of you."

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 66 through 69 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.

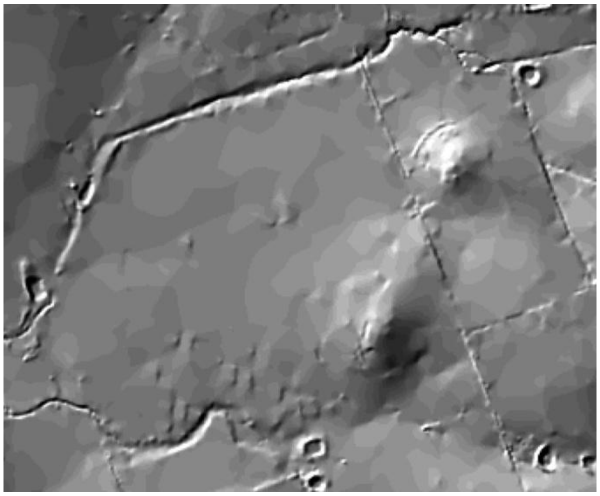


Figure 66. DEM hillshade prior to farm terracing

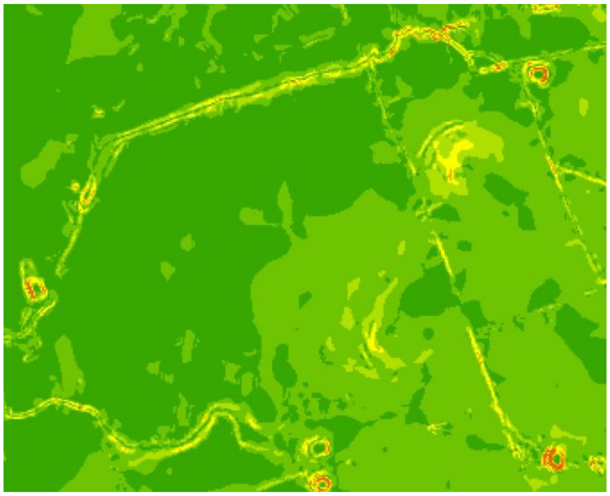


Figure 67. DEM slope gradient prior to farm terracing

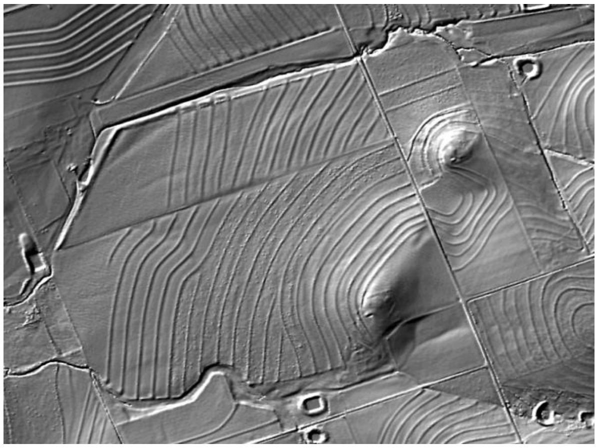


Figure 68. DEM hillshade after farm terracing

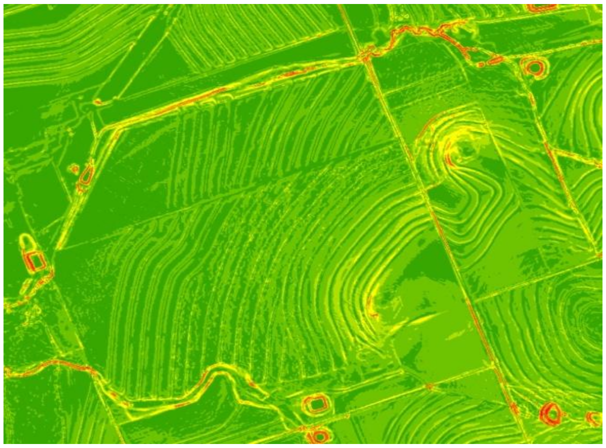


Figure 69. DEM slope gradient after farm terracing

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.

Other Topographic Change Assessments. 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 #15: What is the National Elevation Dataset (NED)?

The National Elevation Dataset (NED) is the primary elevation data product produced and distributed by the U.S. Geological Survey (USGS). Since its inception, the USGS has compiled and published topographic information in many forms, and the NED is the latest development in this long line of products that describe the land surface. The NED provides seamless raster elevation data of the conterminous United States, Alaska, Hawaii, and the island territories. The NED is derived from diverse source data sets that are processed to a specification with a consistent resolution, coordinate system, elevation units, and horizontal and vertical datums. The NED is the logical result of the maturation of the long-standing USGS elevation program, which for many years concentrated on production of map quadrangle-based digital elevation models (DEM). The NED serves as the elevation layer of *The National Map*, and it provides basic elevation information for earth science studies and mapping applications in the U.S.

To maintain seamlessness in its national coverage, the NED uses a raster data model cast in a geographic coordinate system (horizontal locations referenced in decimal degrees of latitude and longitude). The NED employs a multi-resolution structure, with national coverage at a grid spacing of 1-arc-second (approximately 30 meters). The exception is Alaska where lower resolution source data warrant the use of a 2-arc-second spacing. Where higher resolution source data exist, the NED also contains a layer at a post spacing of 1/3-arc-second (approximately 10 meters). Some areas are also available at 1/9-arc-second (approximately 3 meters) post spacing, where high-resolution data exist. The NED does not yet include 1/27-arc-second data (approximately 1 meter) post spacing from highest resolution source data.

The NED production approach ensures that georeferencing of the layers results in properly nested and coincident data across the three resolutions. In the context of the raster data model used for the NED, the area represented by one elevation post in the 1-arc-second layer is represented by nine elevation posts in the 1/3-arc-second layer, and by 81 elevation posts in the 1/9-arc-second layer (Figure 70). Where all three resolution layers can be produced, each layer is constructed independently from the same high-resolution source data using an aggregation method appropriate to the grid spacing being produced. USGS will consider 1/27-arc-second resolution (~1 meter) if justified by user requirements.

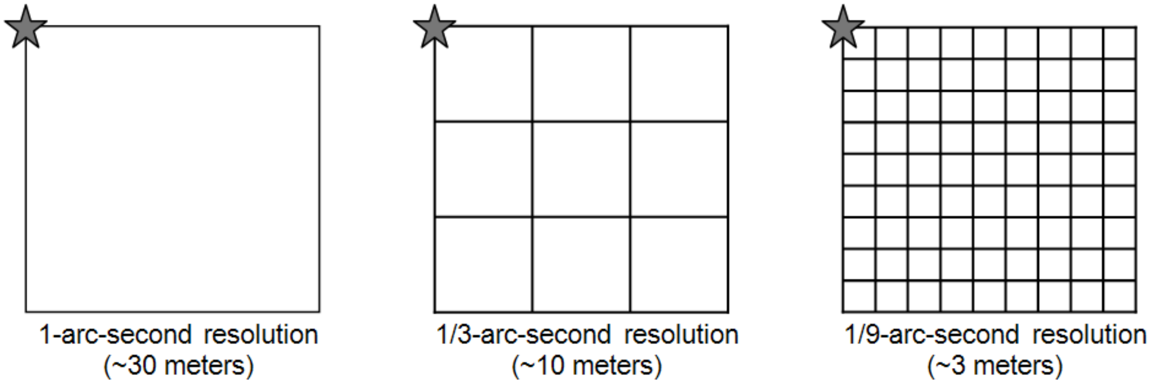


Figure 70. NED nested multi-resolution raster elevation layers. The area represented by one elevation post (or cell) in the 1-arc-second layer is represented by nine elevation posts in the 1/3-arc-second layer and by 81 elevation posts in the 1/9-arc-second layer.

An interactive map server on the NED home page (http://ned.usgs.gov/) allows a user to display the NED data source index, which indicates the date of the most recent update, the resolution of the source data, and the production method of the source data for specific areas. The user can also query the spatially referenced metadata to examine additional information about each file-based DEM used to assemble the NED. The NED Web site also contains documentation on the NED assembly process, accuracy, metadata, standards, data distribution, and release notes. Figure 71 shows the home page for the NED.

The National Elevation Dataset (NED) is the primary elevation data product of the USGS. The NED is a seamless dataset with the best available raster elevation data of the conterminous United States, Alaska, Hawaii, and territorial islands. The NED is updated on a nominal two month cycle to integrate newly available, improved elevation source data. All NED data are public domain. The NED is derived from diverse source data that are processed to a common coordinate system and unit of vertical measure. NED data are distributed in geographic coordinates in units of decimal degrees, and in conformance with the North American Datum of 1983 (NAD 83). All elevation values are in meters and, over the conterminous United States, are referenced to the North American Vertical Datum of 1988 (NAVD 88). The vertical reference will vary in other areas. NED data are available nationally (except for Alaska) at resolutions of 1 arc-second (about 30 meters) and 1/3 arc-second (about 10 meters), and in limited areas at 1/9 arc-second (about 3 meters). In most of Alaska, only lower resolution source data are available. As a result, most NED data for Alaska are at 2-arc-second (about 60 meters) grid spacing, Part of Alaska is available at the 1- and 1/3-arc-second resolution, and plans are in development for a significant improvement in elevation data coverage of the state.

The NED serves as the elevation layer of The National Map, and provides basic elevation information for earth science studies and mapping applications in the United States. Scientists and resource managers use NED data for global change research, hydrologic modeling, resource monitoring, mapping and visualization, and many other applications.

The Seamless Data Distribution System (SDDS) offers seamless data for a user-defined area, in a variety of formats, for online download or media delivery.

Historic Digital Elevation Models (DEMs) are now available.

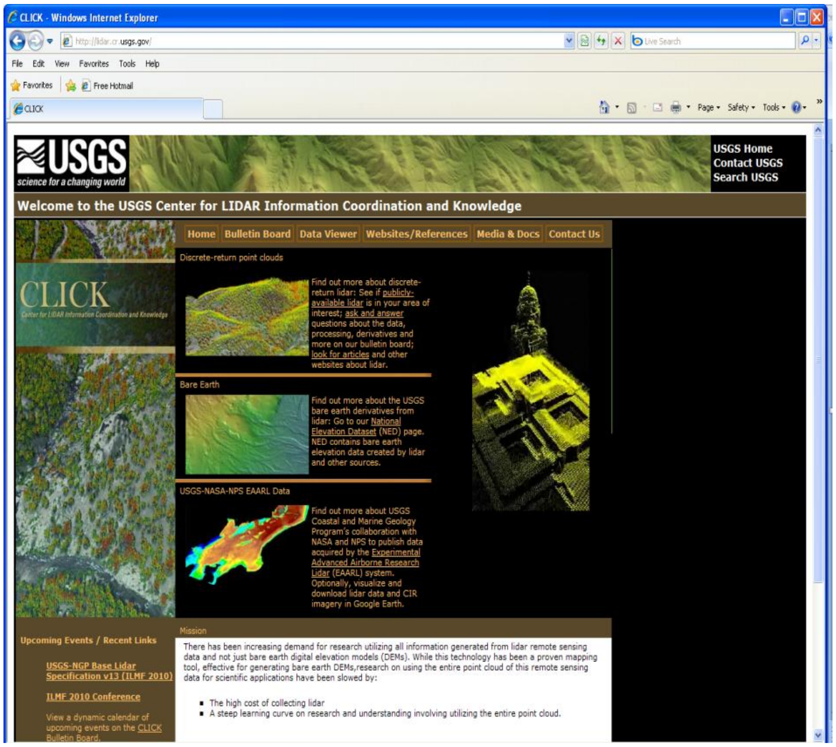
U.S. Department of the Interior | U.S. Geological Survey
URL: http://ned.usgs.gov
Page Contact Information: webmapping@usgs.gov
Page Last Modified: August 2006

Figure 71. National Elevation Dataset (NED) home page

FAQ #16: What is the Center for LiDAR Information Coordination and Knowledge (CLICK)?

USGS' Center for LIDAR Information Coordination and Knowledge (CLICK) is another forum for information exchange and topographic data discovery that benefits the NED. CLICK is a virtual Web-based center with the goal of providing a clearinghouse for LiDAR information and point cloud data.

The CLICK Web site at http://lidar.cr.usgs.gov provides a bulletin board with numerous topics related to LiDAR data for discussion among the community, including topics on bare earth data and the National Digital Elevation Program (NDEP). The site also includes a tool for viewing the coverage of available data and downloading point cloud data, in addition to an extensive list of LiDAR-related Web sites and references. Data acquired for distribution through the CLICK are also used as a source of high-resolution bare earth elevation data to enhance the coverage of the NED 1/9-arc-second layer. In addition, through the CLICK, users have access to the full-return point cloud form of LiDAR data that is included in the NED as bare earth gridded elevation data. The CLICK home page is shown at Figure 72.



Find out more about discrete-return lidar: See if publicly-available lidar is in your area of interest; ask and answer questions about the data, processing, derivatives and more on our bulletin board; look for articles and other websites about lidar.

Find out more about the USGS bare earth derivatives from lidar: Go to our National Elevation Dataset (NED) page. NED contains bare earth elevation data created by lidar and other sources.

Find out more about USGS Coastal and Marine Geology Program's collaboration with NASA and NPS to publish data acquired by the Experimental Advanced Airborne Research Lidar (EAARL) system. Optionally, visualize and download lidar data and CIR imagery in Google Earth.

View a dynamic calendar of upcoming events on the CLICK Bulletin Board.

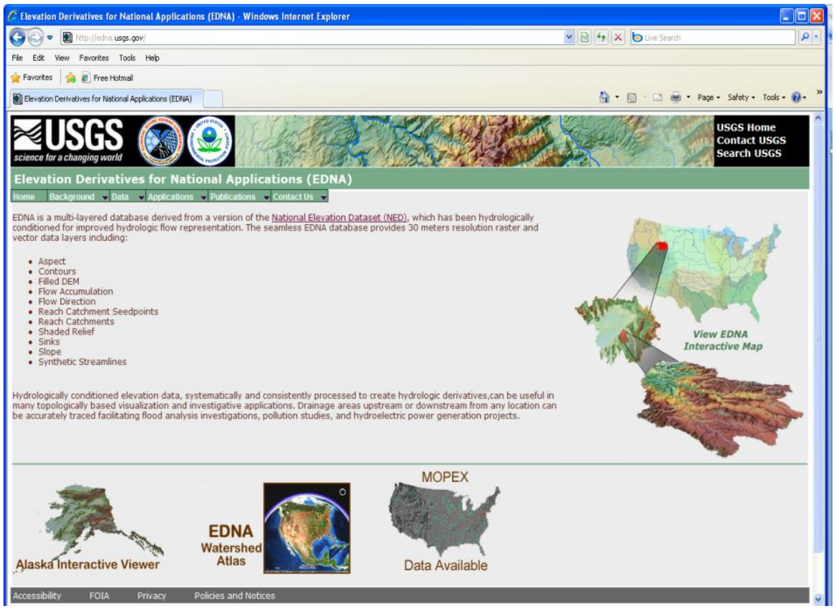
There has been increasing demand for research utilizing all information generated from lidar remote sensing data and not just bare earth digital elevation models (DEMs). While this technology has been a proven mapping tool, effective for generating bare earth DEMs,research on using the entire point cloud of this remote sensing data for scientific applications have been slowed by:

- The high cost of collecting lidar
- A steep learning curve on research and understanding involving utilizing the entire point cloud.

Figure 72. Center for LiDAR Information Coordination and Knowledge (CLICK) home page

FAQ #17: What are Elevation Derivatives for National Applications (EDNA)?

Elevation data are critically important for many hydrologic studies, and these studies are one of the main uses of the NED and associated derived products. The USGS data set known as the Elevation Derivatives for National Applications (EDNA), at http://edna.usgs.gov, is based on the 1-arc-second NED and offers a multi-layered database that was developed specifically for large-area hydrologic modeling applications, including flow direction, flow accumulation, streamlines, catchments, slope, and aspect. The EDNA home page is shown at Figure 73.



EDNA is a multi-layered database derived from a version of the National Elevation Dataset (NED), which has been hydrologically conditioned for improved hydrologic flow representation. The seamless EDNA database provides 30 meters resolution raster and vector data layers including:

- Aspect
- Contours
- Filled DEM
- Flow Accumulation
- Flow Direction
- Reach Catchment Seedpoints
- Reach Catchments
- Shaded Relief
- Sinks
- Slope
- Synthetic Streamlines

Hydrologically conditioned elevation data, systematically and consistently processed to create hydrologic derivatives,can be useful in many topologically based visualization and investigative applications. Drainage areas upstream or downstream from any location can be accurately traced facilitating flood analysis investigations, pollution studies, and hydroelectric power generation projects.

Figure 73. Elevation Derivatives for National Applications (EDNA) home page