What is Lidar Technology

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Lidar returns
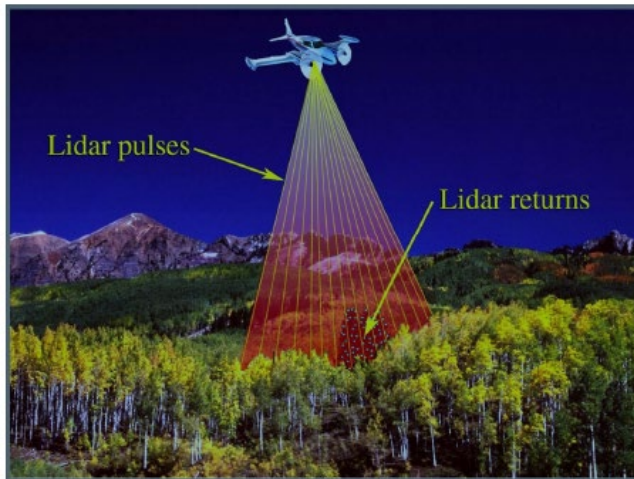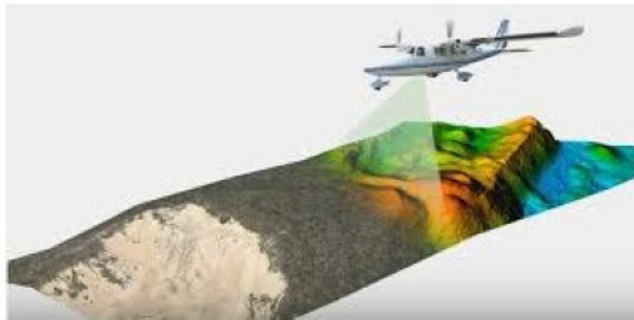
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Lidar 101:

An Introduction to Lidar Technology, Data, and Applications

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1. Introduction

Light detection and ranging (lidar) mapping is an accepted method of generating precise and directly georeferenced spatial information about the shape and surface characteristics of the Earth. Recent advancements in lidar mapping systems and their enabling technologies allow scientists and mapping professionals to examine natural and built environments across a wide range of scales with greater accuracy, precision, and flexibility than ever before. Several national reports issued over the past five years highlight the value and critical need of lidar data. The National Enhanced Elevation Assessment (NEEA) surveyed over 200 federal, state, local, tribal, and nongovernmental organizations to better understand how they use enhanced elevation data, such as lidar data. The over 400 resulting functional activities were grouped into 27 predefined business uses for summary and benefit-cost analysis (NDEP, 2012). Several of these activities will be described in more detail in the applications section of this document.

There are many considerations and trade-offs that must be understood in order to make sound decisions about the procurement, processing, and application of lidar data. This document provides introductory and overview information, as well as in-depth technical information, to support decision-making in all phases of lidar projects. While the information presented here is not comprehensive, it covers aspects of the technology that are the most common subjects of discussion within the coastal management community.

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2. What Is Lidar?

Overview

Lidar has become an established method for collecting very dense and accurate elevation data across landscapes, shallow-water areas, and project sites. This active remote sensing technique is similar to radar but uses laser light pulses instead of radio waves. Lidar is typically "flown" or collected from planes where it can rapidly collect points over large areas (Figure 2-1). Lidar is also collected from ground-based stationary and mobile platforms. These collection techniques are popular within the surveying and engineering communities because they are capable of producing extremely high accuracies and point densities, thus permitting the development of precise, realistic, three-dimensional representations of railroads, roadways, bridges, buildings, breakwaters, and other shoreline structures.

Collection of elevation data using lidar has several advantages over most other techniques. Chief among them are higher resolutions, centimeter accuracies, and ground detection in forested terrain. This section will address 1) the basics of lidar, 2) the terminology, and 3) some examples of how the data are routinely used.
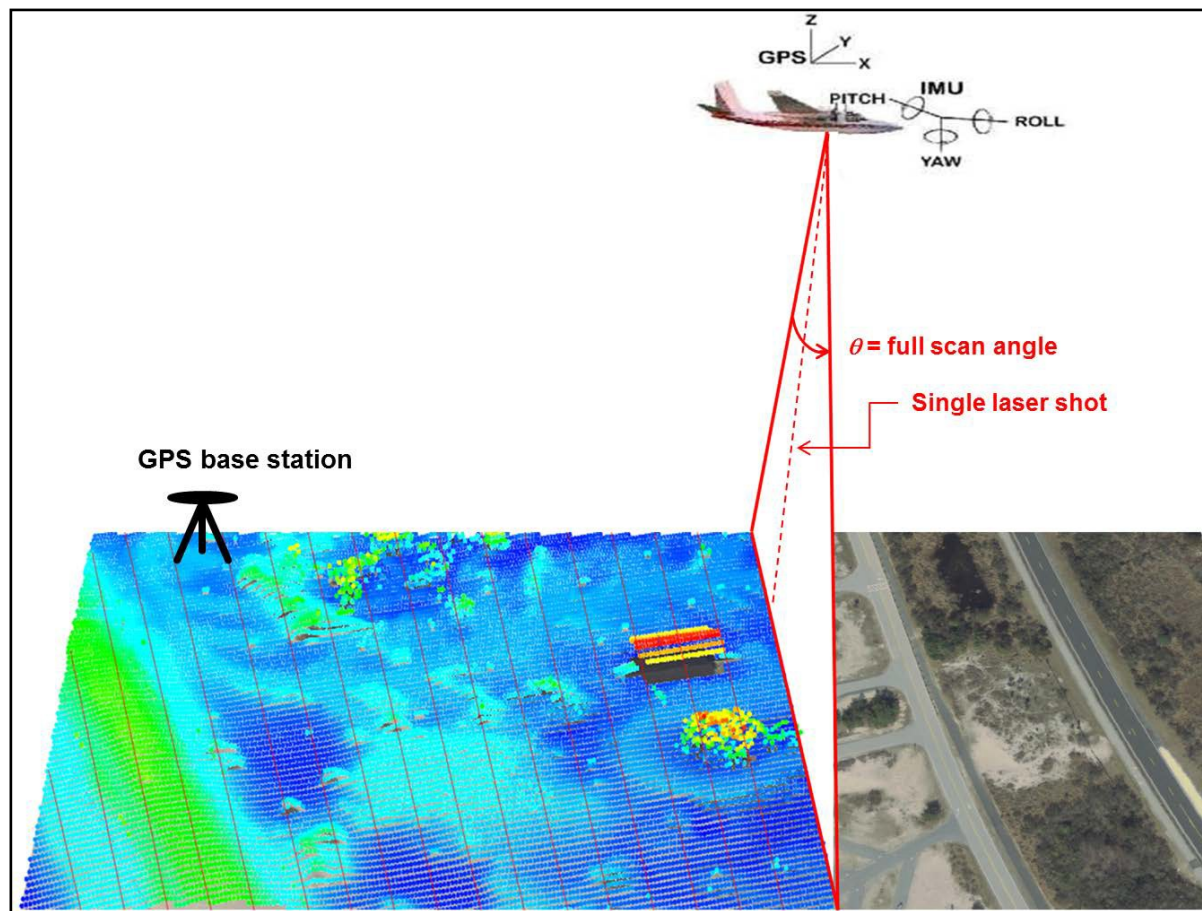

Figure 2-1. Schematic diagram of airborne lidar performing line scanning resulting in parallel lines of measured points (other scan patterns exist, but this one is fairly common)

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What Is Lidar?

Lidar, which is commonly spelled LiDAR and also known as LADAR or laser altimetry, is an acronym for light detection and ranging. It refers to a remote sensing technology that emits intense, focused beams of *light* and measures the time it takes for the reflections to be *detected* by the sensor. This information is used to compute *ranges*, or distances, to objects. In this manner, lidar is analogous to radar (radio detecting and ranging), except that it is based on discrete pulses of laser light. The three-dimensional coordinates (e.g., x,y,z or latitude, longitude, and elevation) of the target objects are computed from 1) the time difference between the laser pulse being emitted and returned, 2) the angle at which the pulse was "fired," and 3) the absolute location of the sensor on or above the surface of the Earth.

There are two classes of remote sensing technologies that are differentiated by the source of energy used to detect a target: passive systems and active systems. Passive systems detect radiation that is generated by an external source of energy, such as the sun, while active systems generate and direct energy toward a target and subsequently detect the radiation. Lidar systems are active systems because they emit pulses of light (i.e. the laser beams) and detect the reflected light. This characteristic allows lidar data to be collected at night when the air is usually clearer and the sky contains less air traffic than in the daytime. In fact, most lidar data are collected at night. Unlike radar, lidar cannot penetrate clouds, rain, or dense haze and must be flown during fair weather.

Lidar instruments can rapidly measure the Earth's surface, at sampling rates greater than 150 kilohertz (i.e., 150,000 pulses per second). The resulting product is a densely spaced network of highly accurate georeferenced elevation points (Figure 2-2)—often called a point cloud—that can be used to generate three-dimensional representations of the Earth's surface and its features. Many lidar systems operate in the near-infrared region of the electromagnetic spectrum, although some sensors also operate in the green band to penetrate water and detect bottom features. These bathymetric lidar systems can be used in areas with relatively clear water to measure seafloor elevations. Typically, lidar-derived elevations have absolute accuracies of about 6 to 12 inches (15 to 30 centimeters) for older data and 4 to 8 inches (10 to 20 centimeters) for more recent data; relative accuracies (e.g., heights of roofs, hills, banks, and dunes) are even better. The description of accuracy is an important aspect of lidar and will be covered in detail in the following sections.
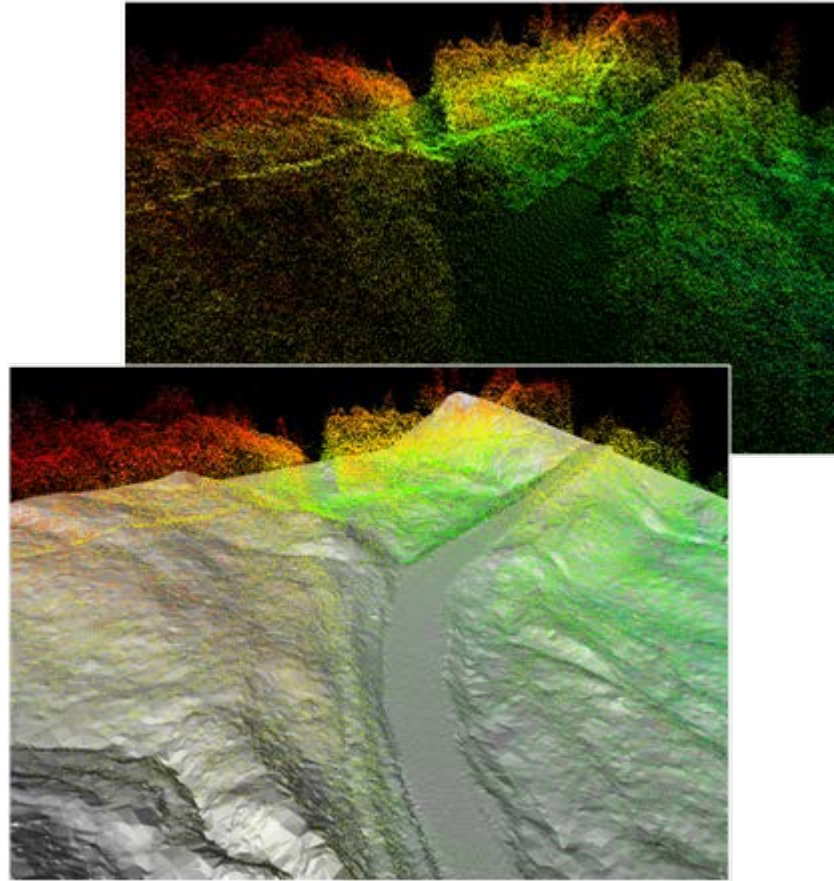
Figure 2-2. Lidar point and surface products

The ability to "see under trees" is a recurring goal when acquiring elevation data using remote sensing data collected from above the Earth's surface (e.g., airplanes or satellites). Most of the larger scale elevation data sets have been generated using remote sensing technologies that cannot penetrate vegetation. Lidar is no exception; however, there are typically enough individual "points" that, even if only a small percentage of them reach the ground through the trees, there are usually enough to provide adequate coverage in forested areas. In effect, lidar is able to see through holes in the canopy or vegetation. Dense forests or areas with complete coverage (as in a rain forest), however, often have few "openings" and so have poor ground representation (i.e., all the points fall on trees and mid-canopy vegetation). A rule of thumb is that if you can look up and see the sky through the trees, then that location can be measured with lidar. For this reason, collecting lidar in "leaf off" conditions is advantageous for measuring ground features in heavily forested areas.

Lidar Platforms

Airborne topographic lidar systems are the most common lidar systems used for generating digital elevation models for large areas. The combination of an airborne platform and a scanning lidar sensor is an effective and efficient technique for collecting elevation data across tens to thousands of square miles. For smaller areas, or where higher density is needed, lidar

sensors can also be deployed on helicopters and ground-based (or water-based) stationary and mobile platforms.

Lidar was first developed as a fixed-position ground-based instrument for studies of atmospheric composition, structure, clouds, and aerosols and remains a powerful tool for climate observations around the world. NOAA and other research organizations operate these instruments to enhance our understanding of climate change. Lidar sensors are also mounted on fixed-position tripods and are used to scan specific targets such as bridges, buildings, and beaches. Tripod-based lidar systems produce point data with centimeter accuracy and are often used for localized terrain-mapping applications that require frequent surveys.

Modern navigation and positioning systems enable the use of water-based and land-based mobile platforms to collect lidar data. These systems are commonly mounted on sport-utility and all-terrain vehicles and may have sensor-to-target ranges greater than a kilometer. Data collected from these platforms are highly accurate and are used extensively to map discrete areas, including railroads, roadways, airports, buildings, utility corridors, harbors, and shorelines.
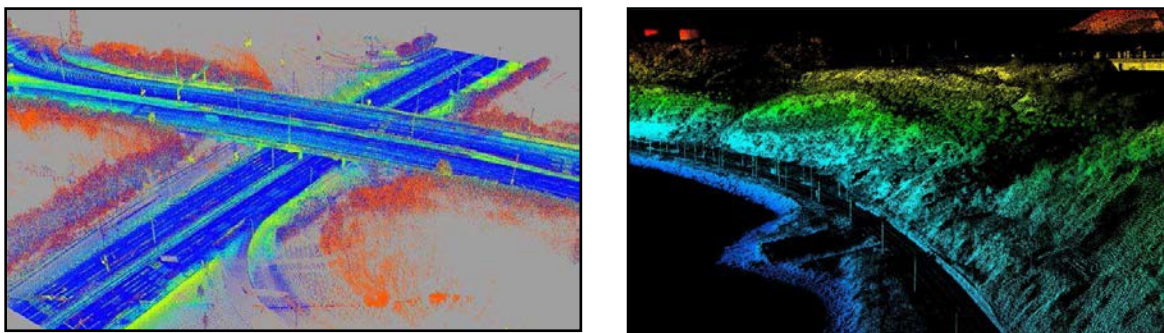

Figure 2-3. Mobile lidar collected from a vehicle (left) and a boat (right) (images courtesy of Sanborn and Fugro)

Airplanes and helicopters are the most common and cost-effective platforms for acquiring lidar data over broad, continuous areas. Airborne lidar data are obtained by mounting a system inside an aircraft and flying over targeted areas. Most airborne platforms can cover about 50 square kilometers per hour and still produce data that meet or exceed the requirements of applications that demand high-accuracy data. Airborne platforms are also ideal for collecting bathymetric data in relatively clear, shallow water. Combined topographic and bathymetric lidar systems on airborne platforms are used to map shoreline and nearshore areas.

Basic Terminology

A discussion of lidar often includes technical terms that describe the level of accuracy (a very important aspect of lidar data), data collection, and the ensuing processing steps.

- **LAS –** abbreviation for laser file format; the LAS file format is a public file format for the interchange of 3-dimensional point cloud data between data users. Although developed primarily for the exchange of lidar point cloud data, this format supports the exchange

of any 3-dimensional x,y,z tuplet. LAS is a binary file format that maintains information specific to the lidar nature of the data while not being overly complex.

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

- **Accuracy$_z$, Fundamental Vertical Accuracy (FVA) –** a measure of the accuracy of the data in open areas at a high level of confidence (95%); calculated from the RMSE using the formula RMSE x 1.96 = FVA.

- **Classification –** data that have been processed to define the type of object that the pulses have reflected off; can be as simple as unclassified (i.e., object not defined) to buildings and high vegetation. The most common is to classify the data set for points that are considered "bare earth" and those that are not (unclassified).

- **Return Number (First/Last Returns) –** many lidar systems are capable of capturing the first, second, third, and ultimately the "last" return from a single laser pulse. The return number can be used to help determine what the reflected pulse is from (e.g., ground, tree, understory).

- **Point Spacing –** how close the laser points are to each other, analogous to the pixel size of an aerial image; also called "posting density" or "nominal point spacing." The point spacing determines the resolution of derived gridded products.

- **Pulse Rate –** the number of discrete laser "shots" per second that the lidar instrument is firing. Systems used in 2012 were capable of up to 300,000 pulses per second. More commonly, the data are captured at approximately 50,000 to 150,000 pulses per second.

- **Intensity Data –** when the laser return is recorded, the strength of the return is also recorded. The values represent how well the object reflected the wavelength of light used by the laser system (e.g., 1,064 nanometer for most commercial topography sensors in the U.S.). These data resemble a black and white photo but cannot be interpreted in exactly the same manner.

- **RTK GPS (Real Time Kinematic GPS) –** satellite navigation that uses the carrier phase (a waveform) that transmits (carries) the Global Positioning System (GPS) signal instead of the GPS signal itself. The actual GPS signal has a frequency of about 1 megahertz, whereas the carrier wave has a frequency of 1500 megahertz, so a difference in signal arrival time is more precise. The carrier phase is more difficult to use (i.e., the equipment is more costly); however, once it has been resolved, it produces a more accurate position in relation to the higher frequency.

- **DEM, or Digital Elevation Model –** a surface created from elevation point data to represent the topography. Often a DEM is more easily used in a geographic information system (GIS) or computer-aided design (CAD) application than the raw point data it is constructed from.

Basic Principles and Techniques

The basic idea (Figure 2-4) is fairly straightforward: measure the time that it takes a laser pulse to strike an object and return to the sensor (which itself has a known location due to direct georeferencing systems), determine the distance using the travel time, record the laser angle, and then, from this information, compute where the reflecting object (e.g., ground, tree, car, etc.) is located in three dimensions.
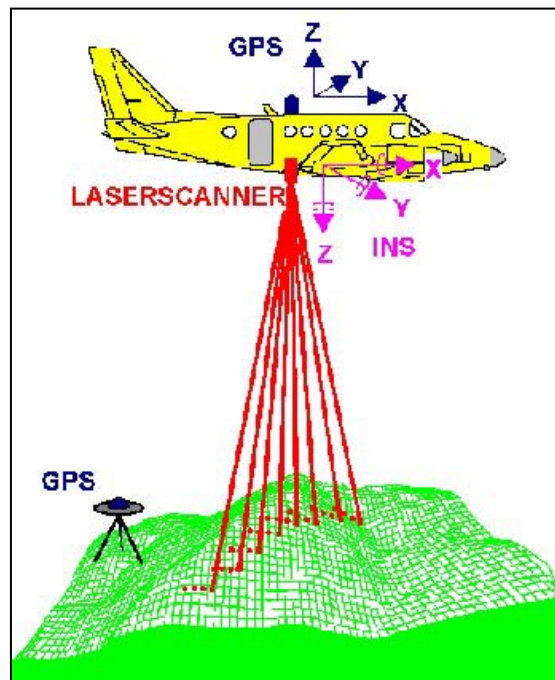

Figure 2-3. Basic lidar data collection schematic from aircraft (Jie Shan, Purdue University)

In reality, to achieve a high level of accuracy, this process is a bit more complicated since it is important to know, within a centimeter or so, where the plane is as it flies at 100 to 200 miles per hour, bumping up and down, while keeping track of hundreds of thousands of lidar pulses per second. Fortunately, several technologies—especially the Global Positioning System (GPS) and precision gyroscopes—came together to make it possible.

Major advancements in Inertial Measuring Units (IMU) or Inertial Navigation Systems (INS) have been instrumental in making the exact positioning of the plane possible. These systems are capable of measuring movement in all directions and parlaying these measurements into a position. They are, however, not perfect, and lose precision after a short time (e.g., 1 second). A very highly sophisticated GPS unit, which records several types of signals from the GPS satellites, is used to "update or reset" the INS or IMU every second or so. The GPS positions are recorded by the plane and also at a ground station with a known position. The ground station provides a "correction" factor to the GPS position recorded by the plane.

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Likewise, lidar systems have advanced considerably. Early commercial units were capable of 10,000 points per second (10 kilohertz) and were large and bulky. Newer systems are more compact, lighter, have higher angular precision, and can process multiple laser returns in the air (i.e., a second laser shot is emitted before returns from the previous laser shot are received), allowing for pulse rates of over 300,000 per second (300 kilohertz).

Multiple return systems, which are common, can capture up to five returns per pulse (Figure 2-5). This can increase the amount of data by 30% or more (100,000 pulses/second ≈ 130,000 returns/second) and increases the ability to look at the three-dimensional structure of the "features above the ground surface," such as the forest canopy and understory.
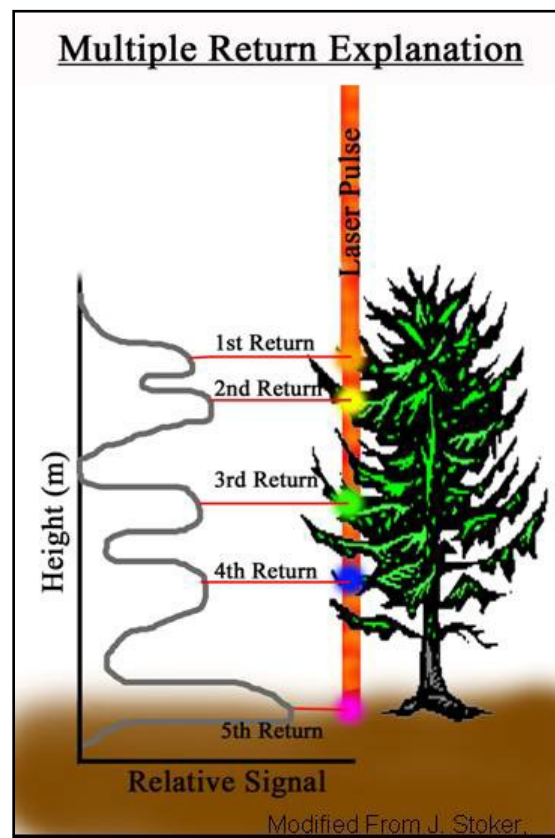

Figure 2-4. Multiple returns from single pulse

Applications – A Quick Overview

Lidar, as a remote sensing technique, has several advantages. Chief among them are high accuracies, high point density, large coverage areas, and the ability of users to resample areas quickly and efficiently. This creates the ability to map discrete changes at a very high resolution, cover large areas uniformly and very accurately, and produce rapid results. The applications below are examples of some common uses of lidar.

- **Updating and Creating Flood Insurance Rate Maps (Figure 2-6)** – This application is a major driver in the development and use of lidar data. The application was largely brought about when hurricanes hit North Carolina and the existing mapped flood zones were quickly shown to be inadequate.
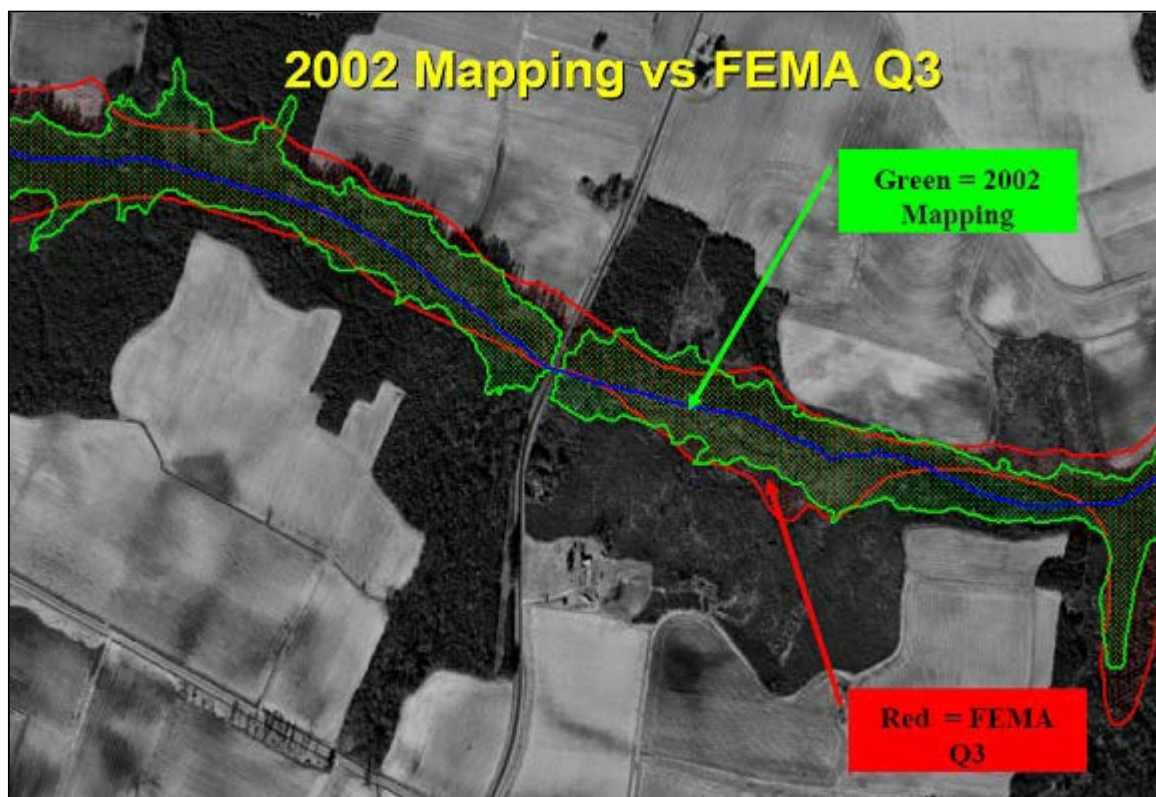

Figure 2-5. Lidar-derived floodplain used to delineate flood boundaries contrasted with previously mapped Federal Emergency Management Agency (FEMA) flood zone boundaries (courtesy of John Dorman, North Carolina Flood Mapping Program)

- **Forest and Tree Studies** – A very costly and time-consuming aspect of timber management is the effort spent in the field measuring trees (Figure 2-7). Typically a sample of trees is measured for a number of parameters and the results are statistically extrapolated throughout the harvest area. Trees must be measured to determine how much wood is present, when it is most appropriate to harvest, and how much to

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harvest. High-resolution, small-footprint lidar has been used to count trees and measure tree height, crown width, and crown depth. From these measurements, the standing volume of timber can be estimated on an individual tree basis, or on a stand level with larger footprint lidar.
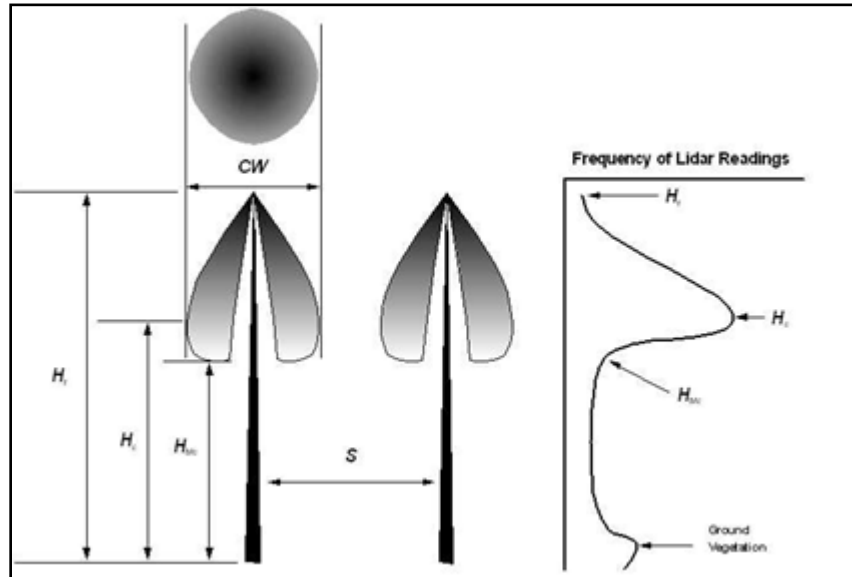

Figure 2-6. Tree canopy information (H = height, CW = crown width, S = spacing) gathered from lidar (courtesy of Mississippi State University)

- **Coastal Change Mapping** – Mapping the coastal zone is an application that highlights the use of lidar data (Figure 2-8) along with GIS layers to increase the utility of both data sets. This highly dynamic region changes on very short timescales (e.g., waves, tides, storms), contains many natural habitats that are highly dependent on elevation, and is densely populated. As a result, the rapid changes can affect significant populations and habitats, both of which are becoming less tolerant to change (i.e., there is less ability to retreat). Lidar data provide the ability to measure specific events as well as longer-term trends. This provides information that can be applied to immediate restoration solutions for critical areas, as well as sustainable planning to minimize future impacts.
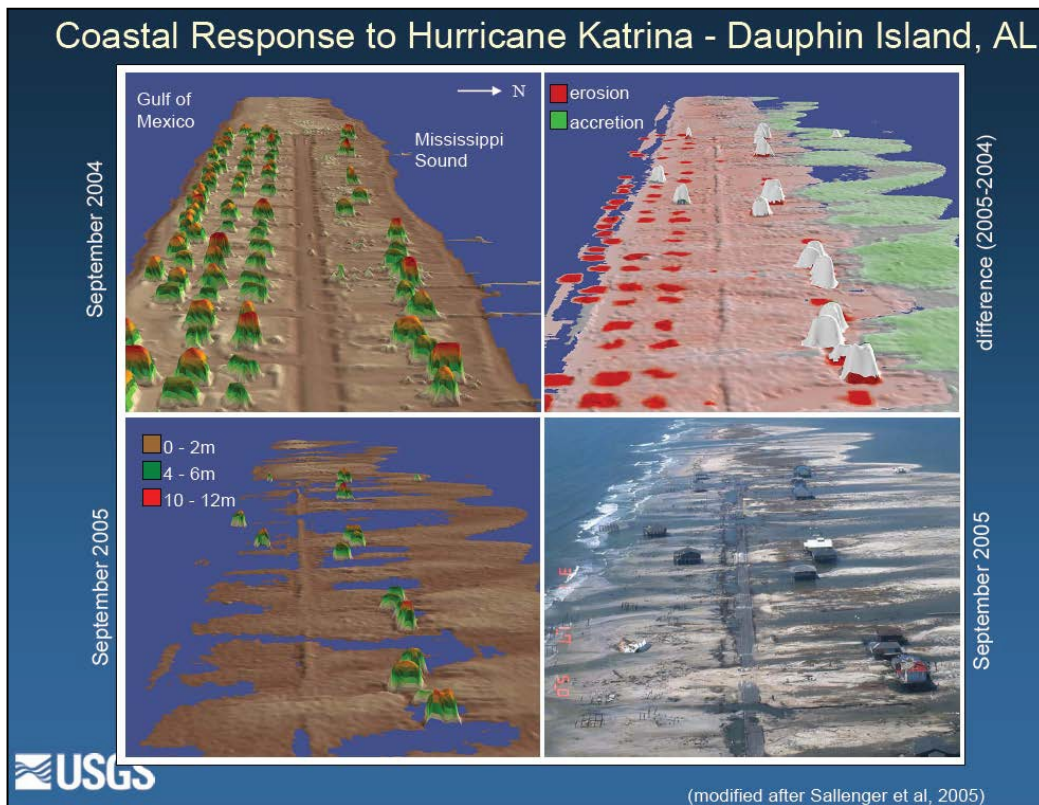
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Figure 2-7. Coastal studies undertaken by the U.S. Geological Survey on Dauphin Island before and following Hurricane Katrina

History

Lidar technology is not new; it was developed over 40 years ago and was initially used for mapping particles in the atmosphere. In this ground-based application, there was far less positional complexity (i.e., the position of the laser did not move) than in airborne mapping. During the 1980s, the development of GPS opened up the applications to moving sensors (airborne lidar). Bathymetric lidar was actually one of the first uses of airborne lidar. The surface of the water provided a "reference" that de-emphasized the absolute location of the airplane. The early 1990s saw the improvement of the IMU and the ability to begin achieving decimeter accuracies. Some of the earlier non-bathymetric airborne applications were in the measurement of glaciers and how they were changing. Ground-based lidar (terrestrial scanning) is also beginning to be used as a way to densely map the three-dimensional nature of features and ground surfaces to an extremely high level of accuracy (1 centimeter).

Summary

Lidar, which can also be referred to as LiDAR, LADAR, airborne laser altimetry, or airborne laser swath mapping, is a widespread and common data layer for a wide variety of applications. Topographic lidar data are typically gathered from airplanes and have benefited from recent advancements in GPS and IMU technology. The technique can provide a dense suite of highly accurate elevation measurements over a large area. While lidar cannot penetrate through

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trees, the point coverage is dense enough to allow for ample ground measurement through small holes in the canopy in most forested environments. Many of the traditional elevation applications benefit from this increased accuracy and coverage, and new applications are being made possible because of the rich data density and high quality.

3. Data Produced by Lidar Sensors

Overview

This section will review some of the aspects that make lidar an attractive data source for coastal mapping and natural resource management applications. The data products from lidar technology can be delivered in several formats. This section looks at the various formats and their differences and the ways in which the data are verified and quantified. In essence, this section will provide an overview of lidar data and the GIS products that are derived directly from it.

Improvements over Previous Data

Lidar data represent several important improvements over previous and commonly used vertical data sets generated for U.S. Geological Survey (USGS) topographic quad maps. The data available through the National Elevation Dataset (NED) have largely been created using photogrammetric techniques. The resulting accuracy of the NED is on the order of 3 meters or 10 feet (Gesch, 2007) with 10- to 30-meter resolution. Photogrammetric elevation generation is a time-consuming, labor-intensive process, especially for high-accuracy products, and therefore is a data set that is not updated often. Moreover, the ability to map areas hidden by or below trees is limited because the technique inherently requires that a location be visible from two vantage points (i.e., two images). The result is that much of the NED are fairly old, have vertical accuracies that limit coastal applications, and have horizontal resolutions that preclude the definition of coastal features. Lidar, while similar in cost to photogrammetry, is a more rapid technique that relies largely on new technology to produce results. Note that the NED is being updated with lidar data as they become available, particularly for the newer 1/9th arc-second (about 3 meters) resolution NED, but as of 2011 only 28% of the U.S. excluding Alaska had lidar coverage.

Vertical Accuracy

The vertical accuracy of lidar data is much better than that of older elevation data that did not include lidar sources. For example, Gesch (2007) reviewed a recent version of the National Elevation Dataset using high-accuracy control points and found that the vertical RMSE was approximately 2.4 meters (8 feet). This is a marked improvement over the NED from 1999 that had an RMSE of 3.7 meters and did not include high-accuracy lidar data. Interestingly, even the older lidar data sets typically have RMSE values of less than 20 centimeters (8 inches) and retain great value due to this level of accuracy. The NED is currently incorporating lidar elevation data sets and will have improved performance and utility in time. The topic of different accuracy measures, including RMSE, is considered in greater detail in Section 5 ("Data Customization and Specification: Accuracy Specification and Tests").

Lidar-derived elevation values in areas with tree coverage are much more dependable than those produced by other techniques because of the sheer number of lidar points. This ability to measure elevations in most obscured areas (Figure 3-1) is one reason the accuracy of lidar is much better (10x) than previously collected data. However, it is important to note that photogrammetric digital elevation model (DEM) data do provide a higher level of confidence

that the points are, indeed, measuring the ground surface. Lidar ground points are determined using automated filters, so while there are significantly more points, they can sometimes fall on non-ground objects or features. For example, there are some ground points (purple in Figure 3-1) in the middle of the lidar profile that appear suspect and would decrease the accuracy of a bare-earth DEM in that area. The vegetation in that area (yellow points) is dense enough that photogrammetry would not have been able to see the ground.
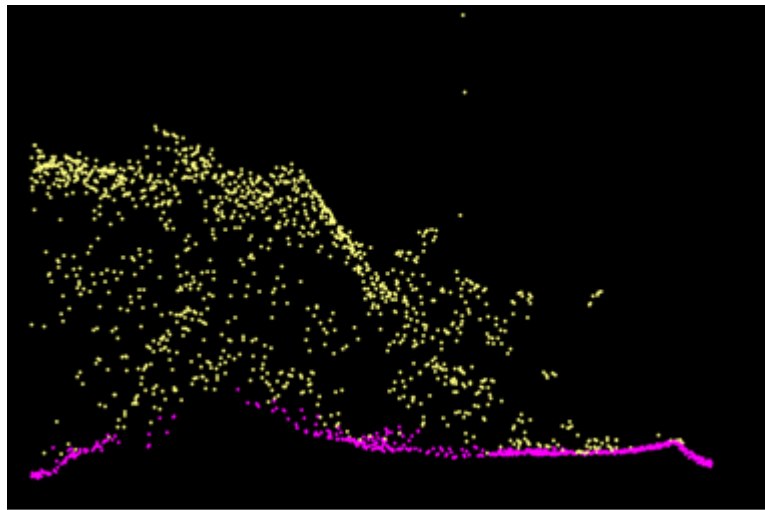

Figure 3-1. Lidar point cloud showing the tops of trees (yellow points) and the ground surface (purple points and dune below trees)

Horizontal Resolution

The horizontal resolution of point spacing of a data set is an important aspect to consider and can impact the tested vertical accuracy. For example, Figures 3-2 and 3-3 depict how high-frequency variability in the ground surface (e.g., slope changes, depressions, gullies, mounds) can be obscured in low-resolution data sets (i.e., large pixels or widely spaced points). In these situations, the vertical accuracy of elevations at the location of the points may be good, while the accuracy of the interpolated surface between points may be poor if significant features are present but not resolved. Thus, the size of features to be measured is a consideration, and since many features that affect drainage patterns are less than 10 meters, which is the resolution of most of the NED data, the ability to discern their actual course, location, and elevation can be difficult. Recent lidar data (i.e., captured within the past five years) usually have a point spacing (horizontal resolution) of between 1 and 2 meters or better. Higher density lidar (multiple points per square meter) can have upwards of eight points per meter and, thus, has a horizontal resolution of 30 centimeters or less. It should be noted that the actual size of the lidar "spot" on the ground or feature is about 30 to 50 centimeters (1 to 1.5 feet) which means that adjacent points actually overlap. This "oversampling" technique is often used to increase the number of points that penetrate vegetation to reach the ground, thus yielding a more accurate representation of the ground surface while also better characterizing the vertical structure of the vegetated overstory.
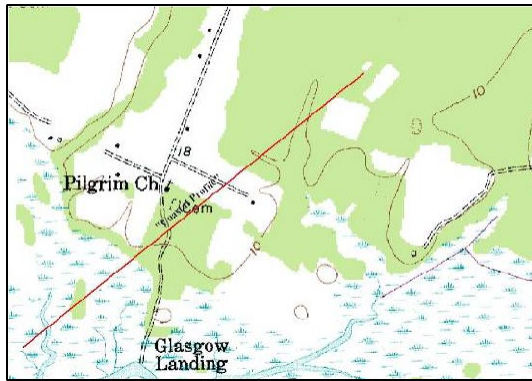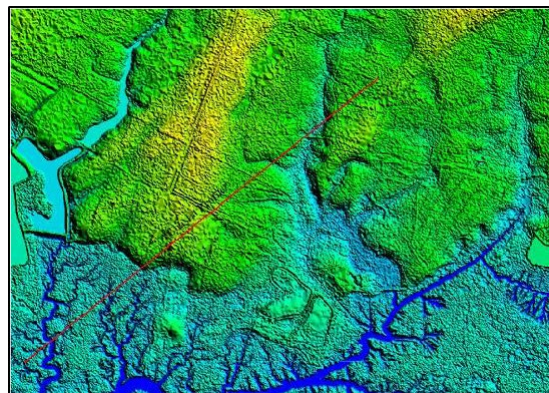
A. Base location with transect (red line)

B. 1 arc-second NED (30 meter)

C. 1/3 arc-second NED (10 meter)

D. Lidar (2 meter)

Figure 3-2. Sequence of images showing a transect used to extract elevation values from three DEMs with different resolutions
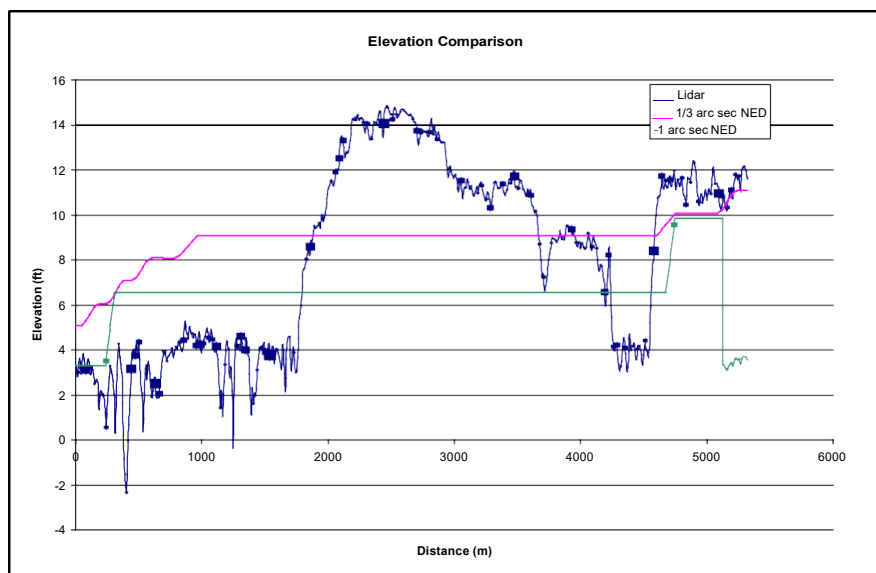

Figure 3-1. Differences in resolution and vertical accuracy between NED and lidar data sets

Temporal Resolution

The time between measurements and the recentness of the data can be as important as data accuracy, especially in the coastal zone, where change, both human and natural, can be dramatic and rapid (Figure 3-4). The highly automated aspect of lidar collection lends itself to rapid deployment and data capture. Temporal resolution is also important for tide-controlled lidar collections. The ability to fly during all hours of the day makes mission planning significantly easier than for photogrammetric techniques.
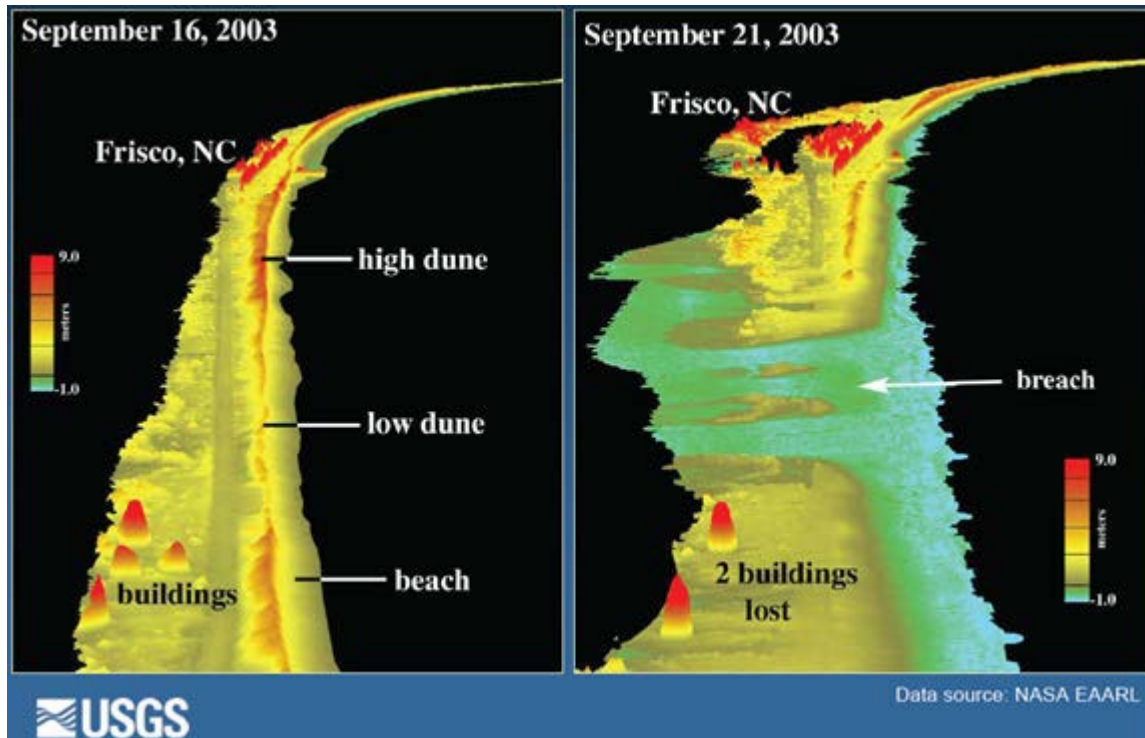

Figure 3-2. Very high temporal resolution data (5 days) help highlight event-related change (courtesy USGS).

Accuracy

Accuracy is one of the primary reasons for use of lidar data. Lidar is an accurate, cost-effective method for collecting topographic elevation data for large areas (Fowler and others, 2007). As a result, determining the required level of data accuracy and documenting the achieved level is an important part of data collection and its subsequent use. Typically a data set is collected with a target accuracy value. The vendor can vary flight and instrument parameters to achieve the required accuracy and cost specifications. Once the data have been collected and processed, they are tested to make sure that the collection and subsequent operations were successful in meeting the desired specifications. Documenting data accuracy is important to ensure proper and widespread use and to maximize data utility. Data accuracy is commonly provided in quality assessment documents and in the metadata.

Accuracy Assessment Techniques

The basic goal of an accuracy assessment is to measure known points on the ground (ground control points, or GCPs) and compare those with points generated from the lidar data. This is often carried out separately for points that fall into different ground cover types. For example, bare-earth lidar errors for points that are in open areas will likely be lower than points under trees. The most common land cover types are bare earth, forest, shrub, urban, and weeds or crops. Bare-earth points are used to judge the overall quality of data collection, because these points typically require very little classification processing. The other land cover types are used to test how well the classification process was able to separate points striking non-ground surfaces from those striking the ground.

In practice, independent measurements (points collected in the field) are compared with a surface created from the lidar points. A surface is used because the lidar points, in most cases, will not fall exactly on the spot where the field measurements were collected. The test surface generated from lidar points is typically created using the triangulated irregular network (TIN) method, which has the least amount of "smoothing." As a result, the lidar elevation is actually a best representation using the three nearest points (i.e., the three points on the triangle). For this reason, it is important that the area being tested not be sloped or irregular; a sloped or irregular surface could potentially bias the elevations. Similarly, the points should be collected in areas where there is a reasonable chance that the lidar can penetrate to the ground (e.g., points should not be collected at the bases of trees where lidar points have little chance of reaching the ground and where the TIN triangles will be large).

Once the values have been compared and the error values generated, several statistical formulas and descriptive terms are used to provide an overview of the data quality. The descriptive terms and their formulas have been developed by several groups and have evolved as the data have become better understood and tested.

Descriptive Terms

The most common terms used to describe a lidar data set's accuracy were described in the "Basic Terminology" section. Four primary documents have helped define the process of measuring, reporting, and defining the accuracy of lidar elevation data. *Guidelines for Digital Elevation Data* (NDEP, 2004), "ASPRS Guidelines: Vertical Accuracy Reporting for Lidar Data" (ASPRS, 2004), and "National Standard for Spatial Data Accuracy" (FGDC, 1998) provide guidance and formulas for determining elevation data accuracy. "Procedure Memorandum No. 61 – Standards for Lidar and Other High Quality Digital Topography" by the Federal Emergency Management Agency (FEMA, 2010) draws on these other data-standard documents and includes specifications for data that are needed for specific flood-mapping applications. The following terms have been developed to provide an overview of the data set as a whole and are often used when defining the quality of data expected for a statement of work. The specific formulas that are used to generate the values for each term are not covered here but can be found in the reference material listed above.

- The **root mean square error (RMSE)** is a statistical measure of variability that is very similar to the standard deviation; in a non-biased data set (i.e., the error is normally

distributed above and below zero) the two values will be the same. This measure is commonly used to describe the variability in lidar elevations. For lidar, the value is calculated directly from the difference between the ground control points and the lidar elevation and for lidar is typically between 5 and 30 centimeters.

- The **Fundamental vertical accuracy (FVA)** is the accuracy value for bare-earth points at a certain confidence level. In this case it is the 95% confidence level and could be phrased as "95% of the bare-earth points meet or exceed the specified accuracy level." This statistic provides information on the quality of the data collection parameters (global quality) because it describes only the bare-earth points, which have not been processed for classification. It can be calculated using RMSE x 1.96 if the errors have a normal distribution, which most bare-earth points follow.

- **Supplemental vertical accuracy (SVA)** is similar to the FVA (95% accuracy), but it is a measure of the individual ground cover types, of which the bare earth is one. The value is typically calculated at the 95th percentile where errors do not follow a normal distribution, where 95% of elevation values have elevation errors equal to or less than the 95th percentile. For example, if 20 points are collected, the worst point (5%) can be removed and the 19th point provided as the SVA value. The SVA value is reported separately for each land cover type tested and, thus, provides more in-depth information than the consolidated vertical accuracy.

- **Consolidated vertical accuracy (CVA)** is also a measure of the accuracy at the 95% level. It is a measure of the entire data set; all the points collected in the various ground types are used together.

Data Types

Like most elevation data, lidar can be stored in a wide variety of formats. The native data are delivered as points (point clouds) that can be processed to create DEMs or TINs (surfaces); the surfaces can then be used to produce contours (lines).
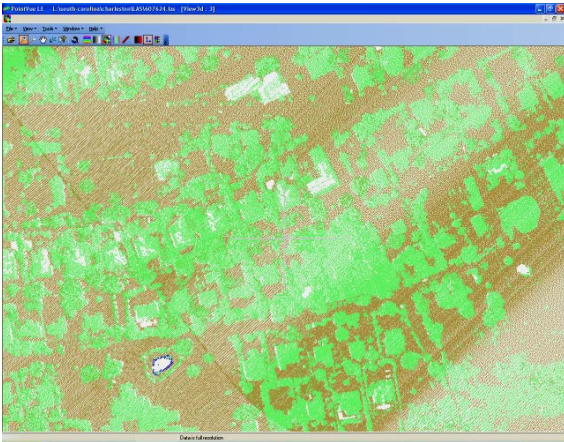
Points

Point data are commonly stored in LAS format, which "is a binary file format that maintains information specific to the LIDAR nature of the data while not being overly complex" (ASPRS, 2007). Lidar data can contain significantly more information than x, y, and z values (Figure 3-5) and may include, among others, the intensity of the returns, the point classification (if done), the number of returns, the time, and the source (flight line) of each point. This information can also come as text files; however, the size of these files can be quite large (several million records with many text characters), making them difficult to work with.
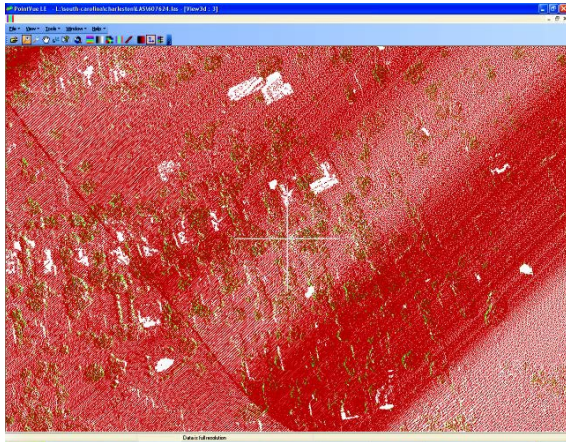
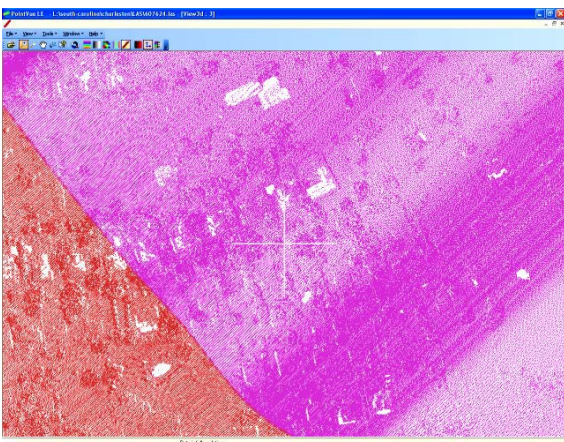FDA, Inc.
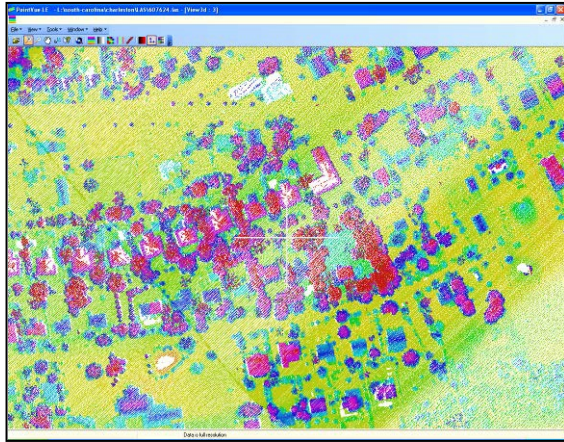
A. Points colored by elevation
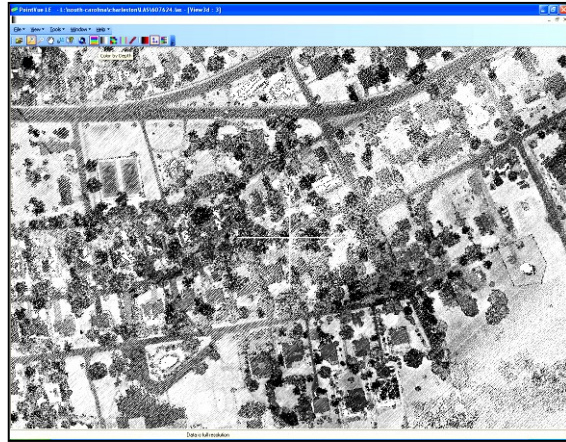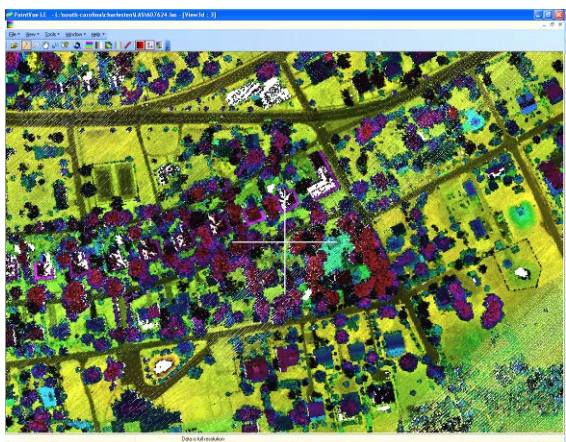
B. Points colored by intensity

C. Points colored by classification

**D. Points colored by return number**

E. Points colored by flight source

F. Intensity and elevation data displayed together

Figure 3-3. Lidar points colored to represent different attributes of the data

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Digital Elevation Models (DEMs)

DEM data are commonly in raster files (Figure 3-6) with formats that include GeoTiff (.tif), Esri Grid (.adf), floating point raster (.flt), or ERDAS Imagine (.img). In some cases the data are available in a TIN format (e.g., Esri TIN). In the raster cases, they are created using point files and can be interpolated using many different techniques.

The techniques used to create DEMs range from simple (e.g., nearest neighbor) to complex (e.g., kriging) gridding routines and can create slightly different surface types (Figure 3-7). The most common are surfaces created from the TIN or the inverse distance weighted (IDW) routines. The appropriate interpolation method depends on the data and the desired use of the DEM.
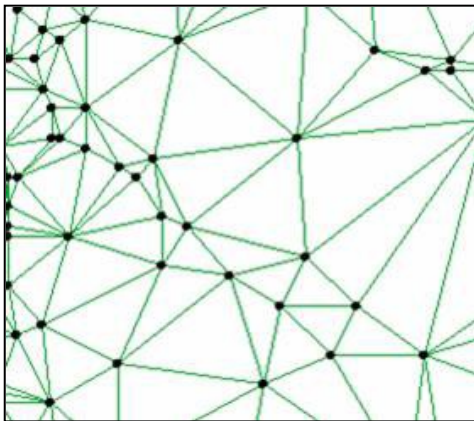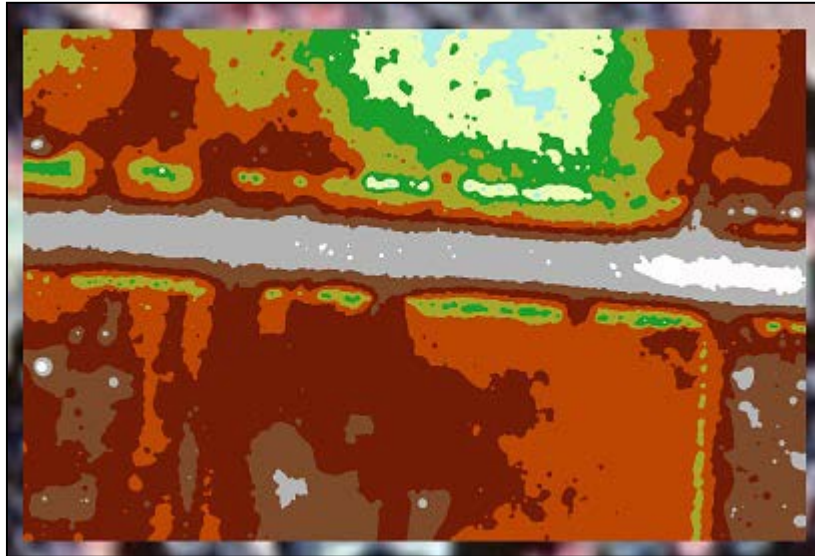

A. Surface represented as a TIN
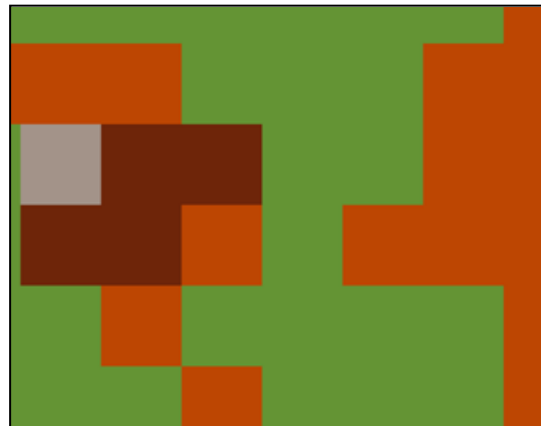
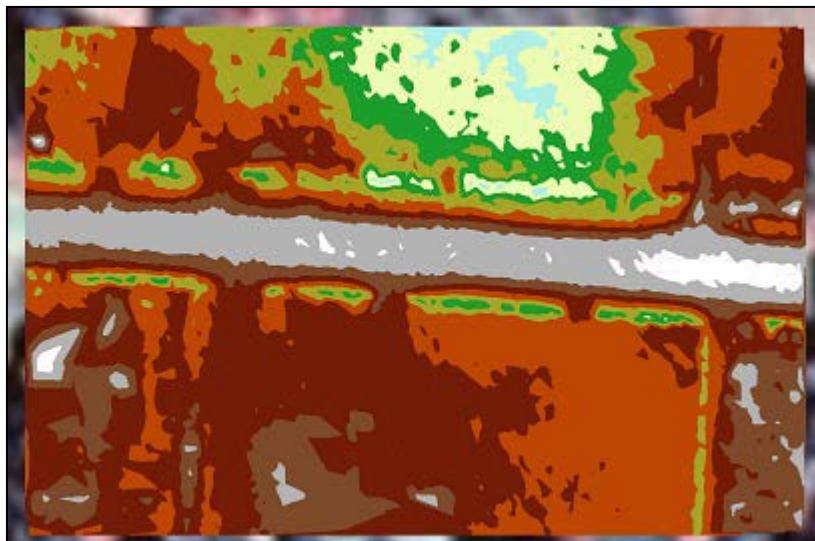**B. Surface represented as a raster (Grid)**

Figure 3-4. Surface format representations

A. Bare-earth points overlain on an aerial image

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B. Raster DEM created with an IDW routine on the points shown in 3-7A

C. TIN created from the points shown in 3-7A

Figure 3-5. DEMs created from the bare-earth. Note the slight differences between the two DEMs.

Hillshade

Hillshading is a technique that helps bring out small variations in elevation data. It is meant to mimic what the ground would look like if the sun were shining on it from a specified angle. This effect can be produced by many of the programs normally used to work with elevation data. The hillshaded image in Figure 3-8 highlights the texture in the TIN surface (Figure 3-7C) and reveals imperfections in the road surface (bumps and ridges) that were not previously evident. This technique is useful during quality assurance reviews and visualization of lidar data.
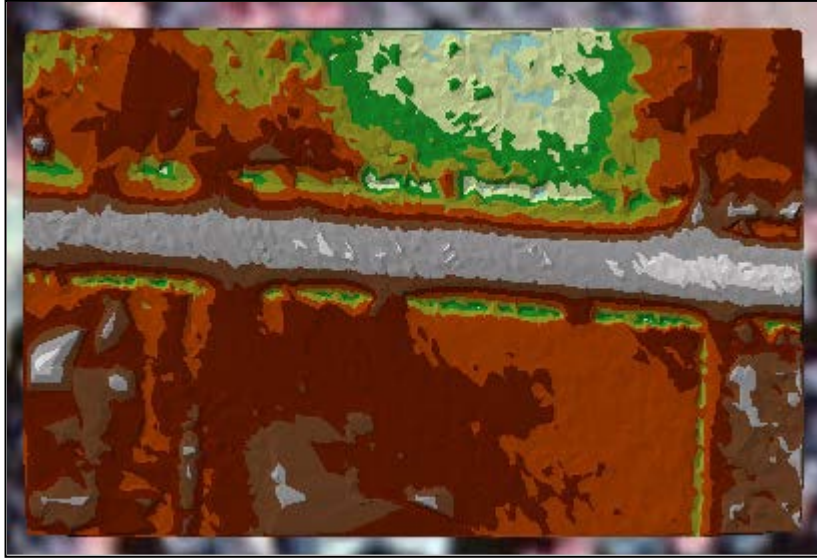
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Figure 3-6. Hillshade of TIN shown in Figure 3-7C

Drape

Draping graphics over elevation often provides additional information and added viewing effect (Figure 3-9). This is simply stretching a "picture" over the "bumpy" elevation surface and using hillshade effects. While a simple technique, it does provide additional visualization clues for feature extraction (e.g., dunes, wetlands).
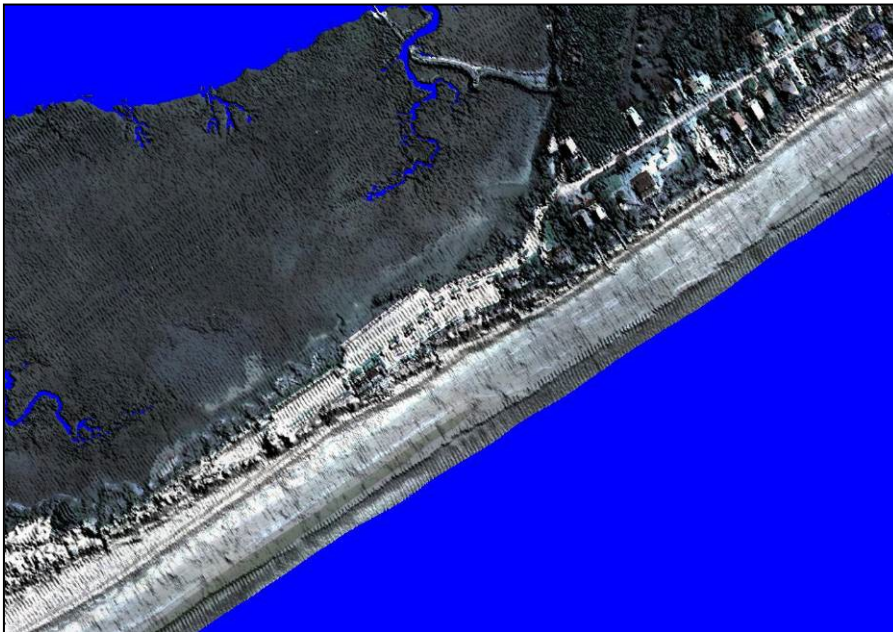

Figure 3-7. Example of an aerial image draped over lidar-generated topography
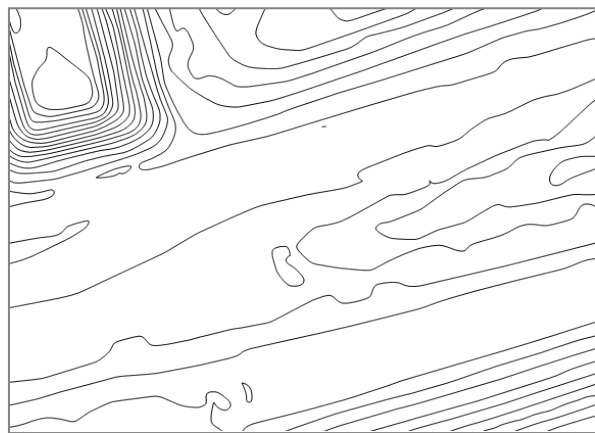
Contours

Contours are commonly available in vector formats (e.g., .shp, .dxf) and are most frequently derived from a pre-constructed DEM or TIN. Contours are among the most commonly used representations for elevations and are found on USGS quad maps. Contours derived directly from lidar data (Figure 3-10A) are accurate but not "clean" and often require a level of interpolation, simplification, smoothing, or manual editing to generate a product that can be more easily interpreted by the human eye (Figure 3-10B). In the process of cleaning and editing the vectors, the position of contours can shift slightly and some small features may even be eliminated. This trade-off between accuracy and interpretability is typically acceptable as lidar-derived contours are most commonly used for cartographic purposes while the original lidar DEMs or TINs are used for analytical purposes.

Highly accurate manually generated breaklines (i.e., vectors delineating slope breaks) are required to achieve pleasing contours with the accuracy of the base lidar data; this is often a very expensive operation. Photogrammetric techniques are commonly used to create three-dimensional breaklines along specific linear features. More recently, a technique known as "lidargrammetry" is being employed. Lidargrammetry uses the intensity values from the lidar points as the "photo" which is processed, using point elevations, into a three-dimensional image. The three-dimensional image can then be used to define breaklines. As a result, separate imagery does not have to be flown for the area where breaklines are required; however, the resulting lidargrammetry breaklines generally do not have as high a resolution as the photogrammetrically derived ones.
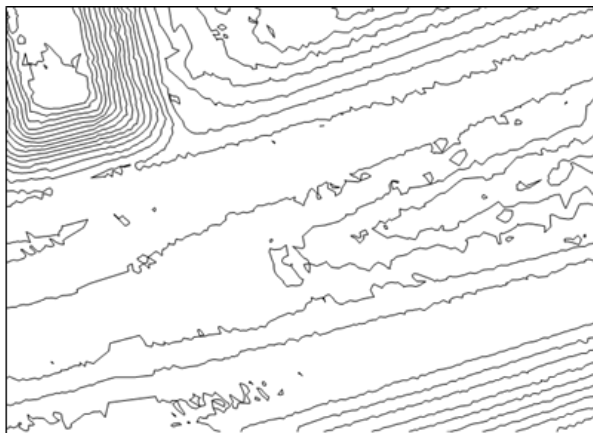
A. Contours derived straight from lidar surface

B. Same contours edited to produce a more intuitive product, but with lowered accuracy

Figure 3-8. Contours generated from lidar data

Although contours can be less accurate than the data they are created from, their generation and specification largely drives the definition of lidar data accuracy. This is a direct result of their widespread use for engineering and other common depictions. In many projects lidar data

are collected to "support the generation of 2 ft contours" or similar statements, which is a way of specifying the vertical accuracy of the data, but not the horizontal resolution. As a rule of thumb, the contour interval that can be supported is about 3.0 x RMSE for American Society for Photogrammetry and Remote Sensing (ASPRS) Class 1 contours or 3.5 x RMSE for National Standard for Spatial Data Accuracy (NSSDA). Both of these standards are based on the conversion from traditional survey methods, which dictated that data used to create contours had to be at least twice as accurate as the contours they defined. So, traditionally, data that were accurate to 1 foot (at the 90% confidence level) could be used to create 2-foot contours; the ASPRS and NSSDA values simply correspond to the 93 and 95% confidence levels respectively. Other ASPRS contour classes exist (e.g., Class 2 and Class 3) and are less stringent than Class 1. Regardless of standard, the widespread use and generation of contours continues to play a large role in the accuracy specifications for lidar data collections.

Summary

Data produced from lidar include the "raw" point data as well as processed derivatives such as contours and surfaces (DEMs). Point data include not only the elevation values, but also classification values, intensity values, and several other point attributes. DEMs are created from the points and can represent bare earth, if the points have been classified, or other surfaces such as the first surface or the last-return surface. DEMs are also used to create contours, which are a commonly used derivative. In short, lidar data are a lot more than simple x,y,z points, and future derivatives, such as "lidargrammetry" and fusion between lidar and imagery (i.e., point values that also include hyperspectral or natural color imagery values), are being developed to take advantage of the high accuracy and increasingly higher data density coverage of the technology.

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4. Use of Lidar Data

Overview

This section will cover the basic use of lidar data in a typical geographic information system (GIS). Normally, the first step is finding the data online or accessing data from a vendor. The next is specifying data parameters, formats, and what types of data derivatives (e.g., intensity, classification) are desired. Once the data have been specified and received, the loading process will vary depending on the format. The process may require some additional software, steps, or plug-ins along the way depending on the data and software. As with all geospatial data, checking the metadata before use is an important consideration; this section will review some important fields for lidar data. The section should provide most users with enough information to begin using the data on their own.

Obtaining Lidar

Existing lidar data are available from numerous public and private entities, and can be obtained freely or at a cost. In either case, it is important to select data that will support the intended use. There are many specifications to consider (e.g., format, projection, datum, classifications) when obtaining lidar data, and the degree of flexibility offered by different sources varies considerably. See Chapter 5 for a full discussion of data specifications.

Many local, state, and federal agencies provide free lidar data online. Two types of lidar products are generally available through these sites: DEMs (raster) and points. Lidar can also be purchased from a contractor. Existing data (that are not in the public domain) is often less expensive than contracting for a new acquisition, but the client has less control over certain specifications such as point spacing and accuracy. If data are to be acquired by a contractor, many of the data specifications will be handled in the statement of work (SOW). The SOW should define, wherever possible, the formats, projections, datums, post-processing (classification) requirements, accuracies, and derived products (e.g., mass points, contours, DEMs) that are desired. Establishing these parameters is a critical step and should be considered carefully.

The data format and other specifications, although important considerations, are often secondary to coverage extent, so simply finding a source of data is the first big step. Web-accessible data discovery tools range in sophistication. For instance, the Puget Sound Lidar Consortium site provides DEM grids through a simple clickable map interface (Figure 4-1). This approach provides easy and fast access to existing grids, but limits the amount of customization available to the end user. More sophisticated data discovery tools frequently use a Web map interface (e.g., Google Maps) or a Web GIS interface (e.g., ArcGIS Server, MapServer). Data can often be selected and downloaded from these sites as well. The USGS Earth Explorer (Figure 4-2) and NOAA's Digital Coast Data Access Viewer (Figure 4-4) provide search and discovery functionality with the option to download data as well. The USGS Earth Explorer can be accessed at the following address: *http://earthexplorer.usgs.gov*. The NOAA Digital Coast Data Access Viewer is discussed in greater detail below and can be accessed through the Digital Coast site at *www.csc.noaa.gov/digitalcoast*.
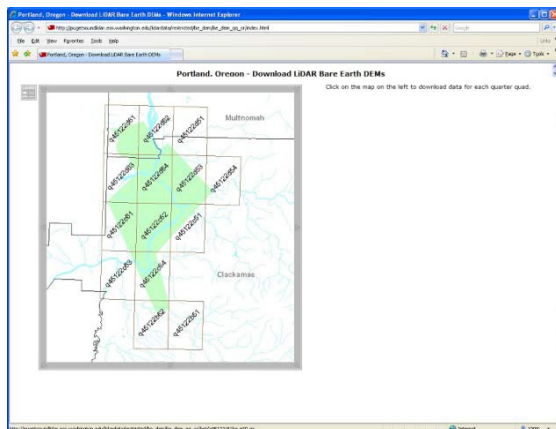
Figure 4-1. Puget Sound Lidar Consortium

Figure 4-1. Earth Explorer

U.S. Interagency Elevation Inventory

The U.S. Interagency Elevation Inventory displays high-accuracy topographic and bathymetric data for the United States and its territories (Figure 4-3). The project is led by NOAA and the U.S. Geological Survey, with contributions from the Federal Emergency Management Agency. The inventory is a comprehensive, nationwide listing of high-accuracy topographic data, including lidar and IfSAR, and bathymetric data, including NOAA hydrographic surveys, multibeam data, and bathymetric lidar. The information provided for each elevation data set includes many attributes such as vertical accuracy, point spacing, and date of collection. Also provided are a point of contact for the data and a direct link to access the data, if available.
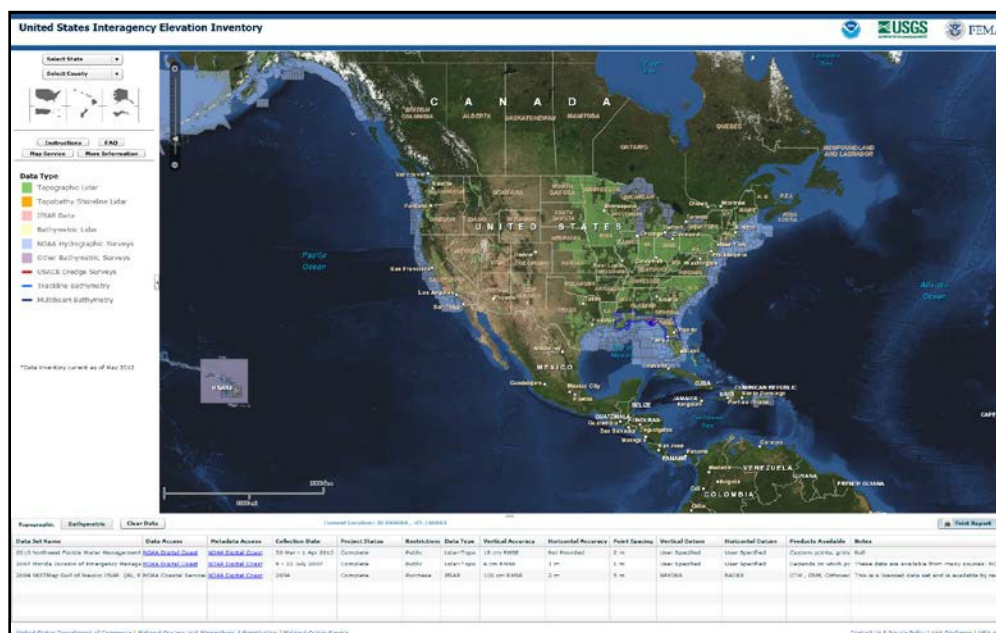

Figure 4-3. U.S. Interagency Elevation Inventory showing footprints of available lidar data

Digital Coast (NOAA Coastal Services Center)

The NOAA Coastal Services Center's online data are provided via the Digital Coast (Figure 4-4) at *www.csc.noaa.gov/digitalcoast*. This system provides data in several point, line, and raster formats. Additionally, only data from the user's specified area of interest is delivered, which helps in minimizing download sizes and subsequent hardware resources. The interface includes a location search and a map search to define the area of interest. A detailed example of how to access this data source is provided in the *Lidar Provisioning Guidance for the Digital Coast Data Access Viewer* (NOAA, 2011).
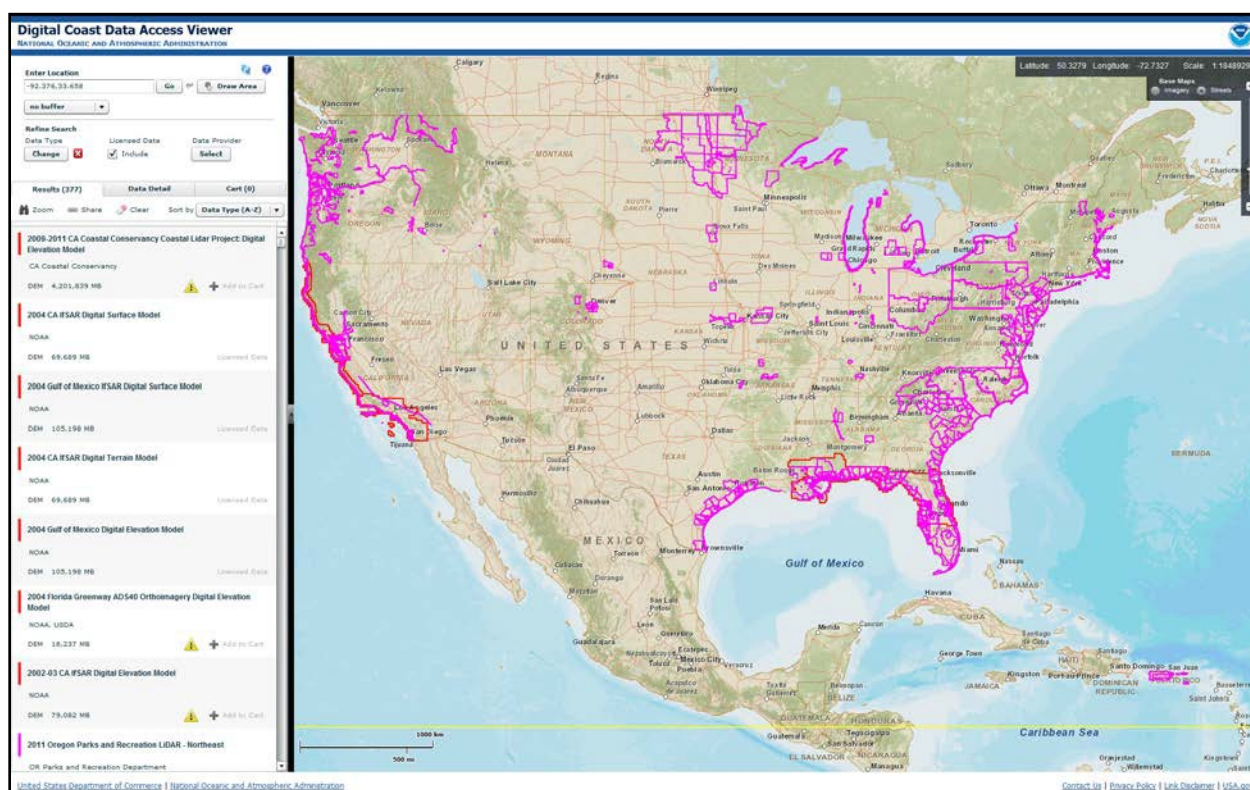

Figure 4-2. Lidar coverage in the Digital Coast Data Access Viewer (as of 2012)

Loading Data into a GIS

Once the data have been accessed and downloaded as a point file, a raster file, or line file, they are commonly viewed and manipulated in a GIS system with additional data. This highlights the importance of specifying data in a format, projection, unit of measure, and datum that are compatible with the additional data being used, or at least knowing these values.

One of the most commonly used GIS systems is Esri's ArcGIS. ArcGIS is a powerful and flexible environment for overlaying lidar-derived contours and surfaces with other common GIS data layers and performing analysis. Other GIS software packages that handle lidar data well include Global Mapper and AutoCad Map (Land Survey). Additionally, many lidar-specific software

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packages are available as plug-ins for ArcGIS or as stand-alone programs. These packages, such as LAStools, provide sophisticated and often very efficient algorithms for data analysis and subsequent export of products to common GIS formats. Typically, the lidar-specific packages will offer more capability for working with the point data than the more general GIS or CAD oriented packages.

Lidar Data and ArcGIS

Esri's ArcGIS for Desktop software has not traditionally been the easiest or the most robust system to use with lidar point data because of the complexity and sheer volume of points in typical lidar data sets. However, this software is the geospatial package that is used most widely within the coastal management community, so NOAA is focusing on it instead of other packages that may be more lidar-specific. With the release of ArcGIS 9.2, Esri introduced terrain data sets that provided limited capabilities to work with LAS files. The release of ArcGIS 10.1 introduced much more robust support for lidar point clouds, allowing users to incorporate LAS data into three container types: terrain data sets, mosaic data sets, and LAS data sets. The latter container type points to the LAS files on disk and allows users to render point clouds and triangulated surfaces in two and three dimensions, perform a variety of analytic operations, display filtered and classed points, edit points, and combine with breaklines during surface development. It is important to note that Esri exposes different levels of LAS functionality through different license levels and software extensions. The most useful functionality begins with the ArcGIS for Desktop Standard license (formerly ArcEditor), and the Spatial Analyst and 3D Analyst extensions add the capabilities for most data analysis and visualization tasks.

Working with lidar data in ArcGIS requires careful planning and consideration for compatibility. Lidar data are represented by several different data structures (e.g., points, lines, surfaces) and can be delivered to users in many different formats. However, not all formats are supported by ArcGIS, so users must understand which formats are compatible with their specific version and license level. For example, ASCII text or LAS files are the most common point formats, but only certain versions (i.e., ArcGIS 10.1 and later) can read and efficiently process LAS files, and a third-party extension would be needed to read the compressed LAZ version of LAS. Raster (gridded) data are sometimes available as Esri Grids, but not consistently; often ASCII grid or binary raster (nonproprietary) formats are the only available types and may require conversion to other formats before they can be used. Contours, on the other hand, are typically available as Esri-supported shapefiles.

Contours

Contours can be generated in ArcGIS (with Spatial Analyst or 3D Analyst) or downloaded as products from online sources (e.g., Digital Coast) as either .shp or .dxf formats. The following example will use Digital Coast-supplied contours. Creation of contours from a surface generated using Spatial Analyst will be covered later in the "Surfaces" section.

No matter how the contours are acquired, a surface is typically required to create them. The surface can be generated using several different specifications or techniques (see "Surfaces"), which can affect the location, geometry, and look of the contours. For example, in the Digital Coast Data Access Viewer interface, several different techniques are available to assign an

elevation to each raster cell from which the contours are created. Once generated, the process of displaying contours in ArcGIS is the same as for any .shp or dxf.

Unclassified data, or data not filtered to create a bare-earth data set, will produce extremely noisy and large contour data sets (Figure 4-5). If the lidar has not been processed to define ground points, the resulting contours will show vegetation and structures, as well as the bare ground (Figure 4-6A). This is a common problem; however, if the area is small, the contours that fall on houses can be removed (or classified) manually using photos, the lidar intensity images (Figure 4-6B), or obvious "house" signatures. The result is a product that may be more useful for examining ground features or modeling the local hydrology.
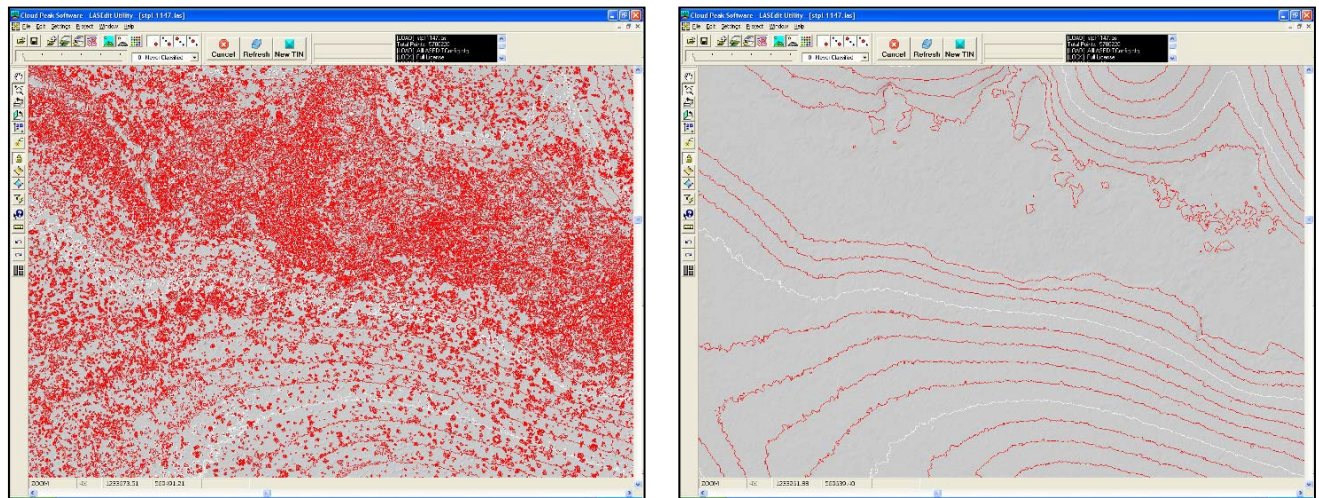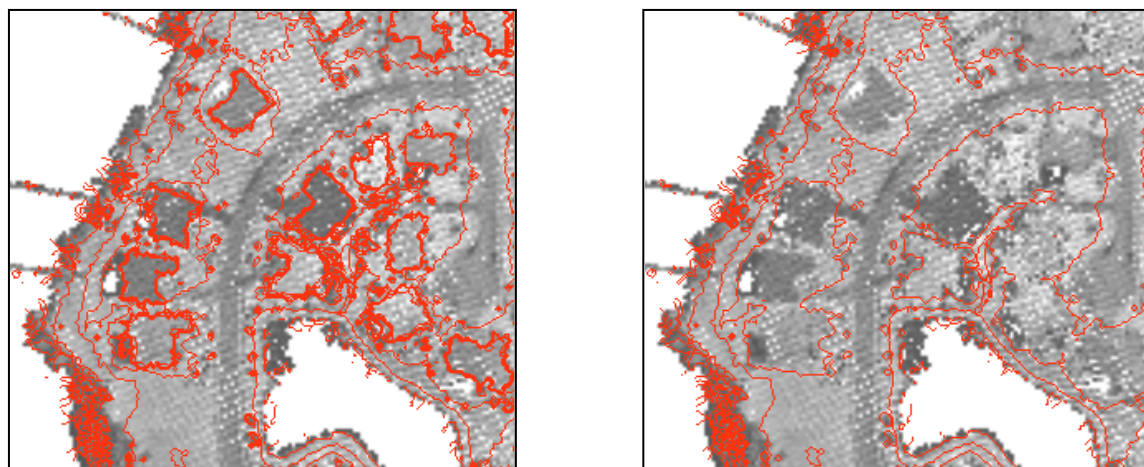

Figure 4-3. Unfiltered (left) and bare-earth (right) contour data sets of the same area


A. As-received contours overlain on intensity image   **B. Contours manually edited in ArcMap to remove houses**

**Figure 4-4. Small-scale editing of contours**

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Even with classified data, the contours generated will probably lack the familiar "pleasing" look (Figure 4-7A). The look can be enhanced by "simplifying" or smoothing them in ArcGIS (Figure 4-7B); however, this will lower the accuracy of the contours. To fully improve the contours, while maintaining the same accuracy, additional information is required. Breaklines can be incorporated to bring out subtle features and improve visual appeal (Figure 4-7C and 4-7D).
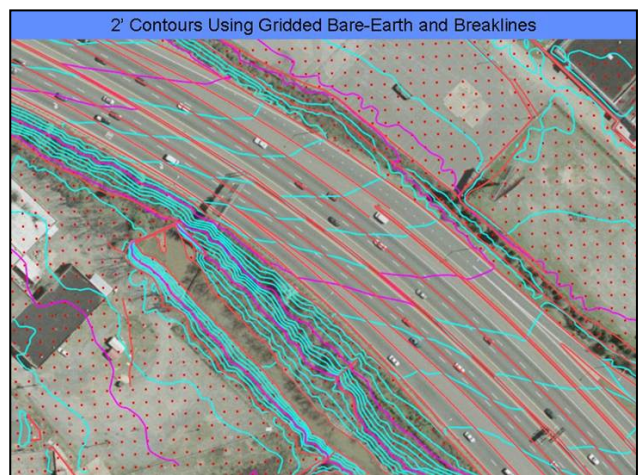

A. Raw contours
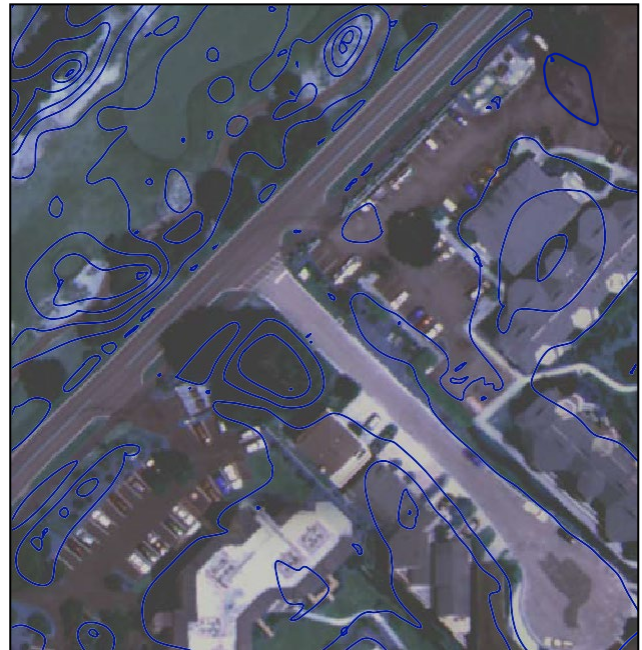
B. Smoothed contours
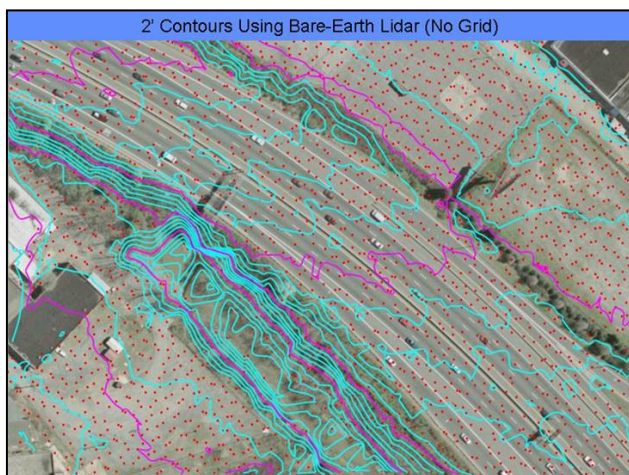
C. Raw lidar points and contours (courtesy Fugro-EarthData)

D. Gridded data, breaklines (red lines), and resulting contours (courtesy Fugro-EarthData)

Figure 4-5. Bare-earth contours

There are several different standards for classifying the accuracy of contours, and lidar data are often collected to meet these specific standards. Table 4-1 is provided to show how the root mean square error (RMSE) accuracy (in centimeters) of lidar data compares to the generation of contours (in feet) based on different classes and standards. In general, most lidar is collected to meet or exceed the specifications for 2-foot contours at either ASPRS Class 1 or National Map Accuracy Standards (NMAS). And, again, this level of data accuracy will not provide "pleasing" contours; ancillary data and manual editing are required to produce pleasing contours within the accuracy guidelines provided.

Table 4-1. Contour Intervals (CI) in Feet and Various Accuracy Standards in Centimeters

CI [ft]	RMSE (NSSDA 1998) [cm]			
	NMAS '47	ASPRS Class 1	ASPRS Class 2	ASPRS Class 3
1	9.3	10.2	20.3	30.5
2	18.5	20.3	40.6	61.0
3	27.8	30.5	61.0	91.4

Points

The other vector format is points, which is also the native lidar data format. The two common file formats for points are LAS and ASCII. There are size and format issues when using points in ArcGIS that can complicate the process. Newer releases of ArcGIS (9.2 and above) have new data containers that significantly aid in lidar point use. A lidar point file for a relatively small-sized area of investigation may hold 1 to 2 million points, which can, if in a shapefile format, slow the application appreciably. For this reason, it is important to either exclude outlying points from the project or select only the type of points you are interested in (e.g., if interested in topography only, minimize points to only ground classified, or last returns).

ASCII files (i.e., delimited text) commonly have a comma-separated format as in this example:

```
Longitude,Latitude,Elevation
-75.998765,36.463294,12.54
-75.998766,36.463293,12.36
```

Opening an ASCII point file in ArcGIS generally requires the following:

1. Converting to a comma-delimited text format, database, or spreadsheet format.
2. Adding the tabular data (in ArcGIS: **File > Add Data > Add XY Data**) and specifying the correct x, y, and z fields and coordinate system.

> *Tip: Creating the .csv or .dbf file can be accomplished using common programs such as Microsoft Excel or Access. If the file is even moderately*

*sized (beyond a neighborhood block), Microsoft Access is the better option, since Microsoft Excel is limited to about 65,000 points. Import the xyz.txt file in Access to a new table and then export that file as a .dbf (highlight the table; select **File > Export**; select .**dbf** format).*

LAS point files are binary formats that can be read by ArcGIS (prior to version 10.1) but require preprocessing using ArcGIS tools or a third-party utility. Several free utilities are available to help bring LAS data into ArcGIS. The simplest is called LAS Reader for ArcGIS (*www.geocue.com/support/utilities.html*), which allows ArcGIS to read LAS files natively (Figure 4-8). With this utility, LAS files appear when viewing data files in ArcCatalog or when adding data in ArcMap. Another option is the LAStools LiDAR processing toolbox (from *http://rapidlasso.com*) that allows leveraging the efficient collection of LAStools command-line tools from ArcGIS. The toolbox is simply added to ArcToolbox, and different processing tools are available to generate three-dimensional multi-point and point shapefiles, contours, DEMs, and more. Note that LAStools are freely available for evaluation purposes, but licensing restrictions apply for certain use cases (see *http://lastools.org/LICENSE.txt*).

The fields of the attribute tables for files loaded as a .dbf (Figure 4-9) and with LAS Reader (Figure 4-10) highlight the differences among techniques for importing the data into the GIS. The LAS Reader and the LAStools "las2shp" programs assign the points a 3D coordinate (PointZ; Figures 4-10); the database method does not (Figure 4-9) but includes an elevation field in the attribute table that can be selected to define a symbology or create a surface.
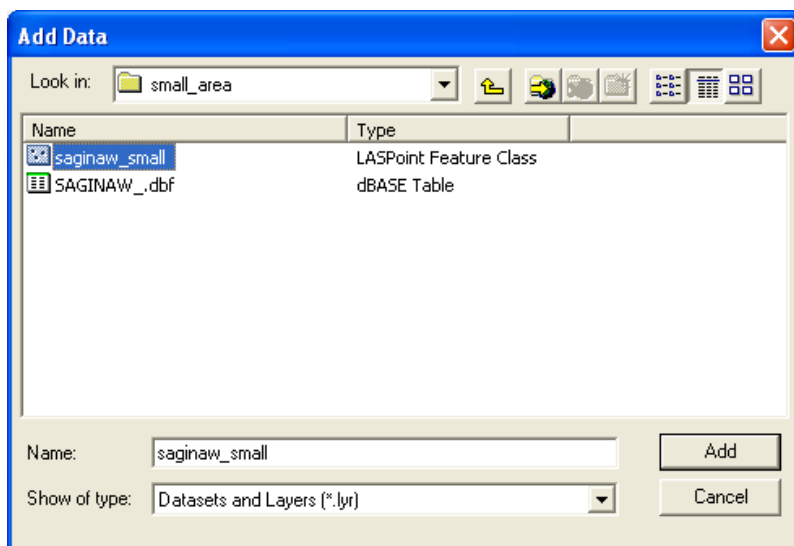

Figure 4-6. Lidar being loaded as native layer (LAS) using LAS Reader and as an XYZ Dbase table

Figure 4-7. XYZ Attribute information imported from Dbase table

Figure 4-8. LAS attribute information – includes elevation, classification, intensity, and return number

Once points have been added, they can be used independently to symbolize elevation (Figure 4-11) or used for further analysis with one of the ArcGIS extensions to create surfaces or contours (See "Surfaces"). A simple DEM (Figure 4-12) can be created by using ArcToolbox (Conversion Tools > To Raster > Feature to Raster) if the Spatial Analyst or 3D Analyst extensions are not available. Intensity can also be symbolized (Figure 4-13) if available in the point attributes to create a "pseudo image."
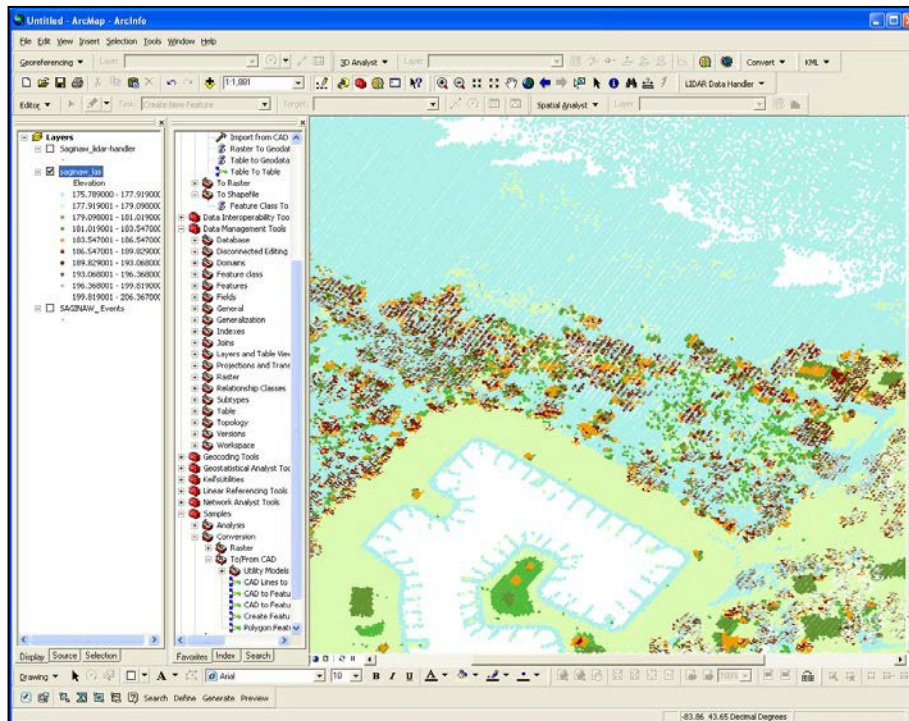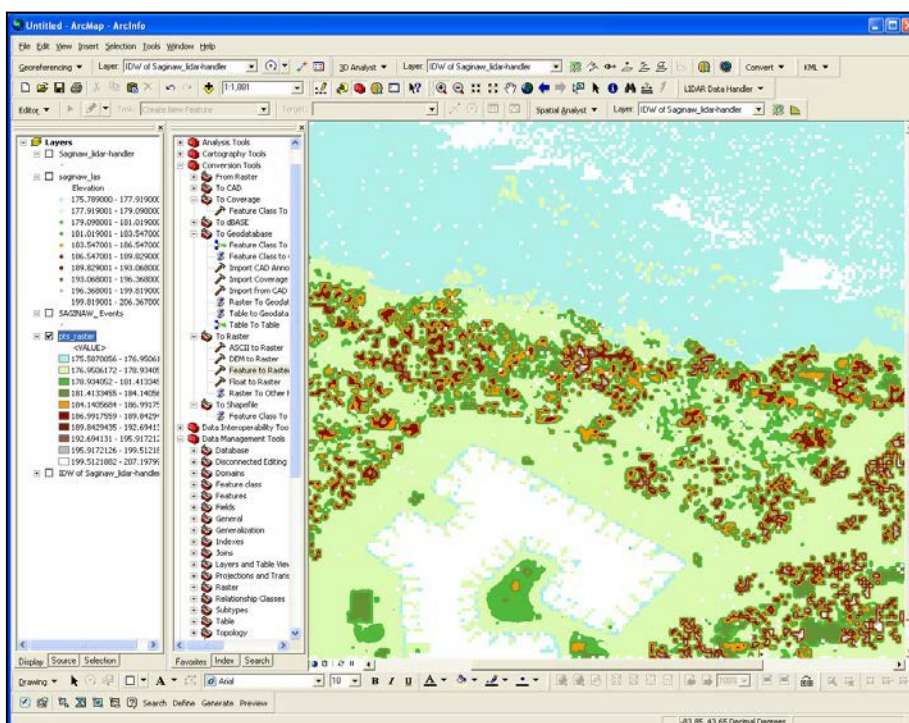
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Figure 4-11. Points colored by elevation

Figure 4-9. Points rasterized and colored by elevation to create a simple DEM
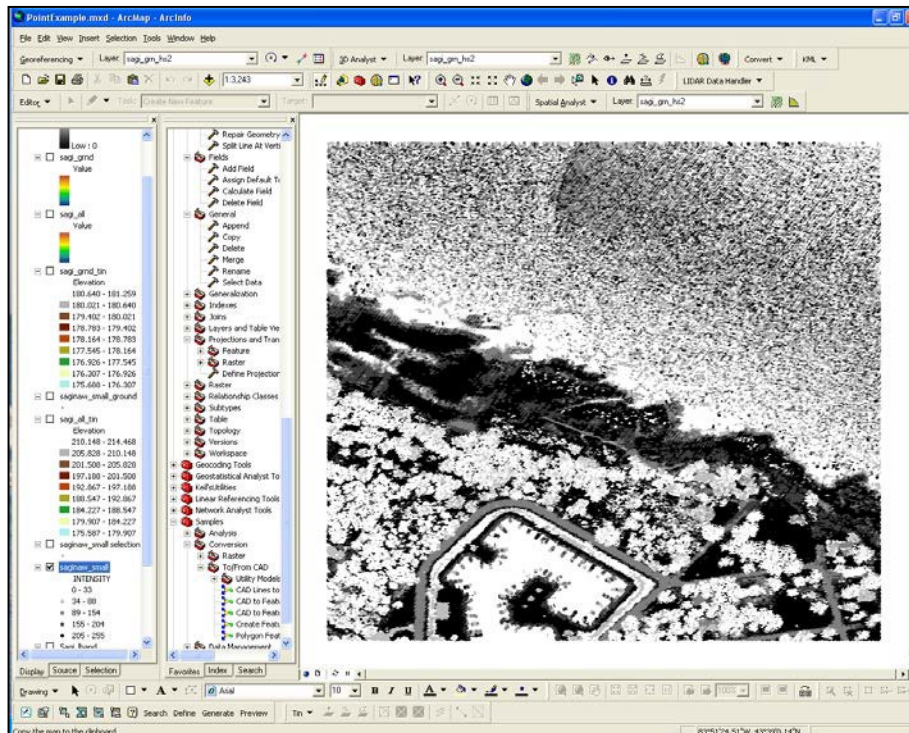
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Figure 4-10. Points colored by intensity values

Surfaces (Grids) – The most common lidar product is a grid or raster elevation surface. Surfaces developed from lidar data highlight the intrinsic value of the data (i.e., high accuracy over large areas), and are the basis for multiple forms of derived products.

Several data monikers or descriptions are used to explain elevation products or surfaces. The three terms often referred to when describing an elevation product are

- a digital elevation model (DEM),

- a digital terrain model (DTM), and

- a digital surface model (DSM).

The term "DEM" is typically used as a general description of an elevation surface. It is often used in conjunction with a specific or additional description, such as a bare-earth DEM or topo-bathy DEM, which provides further information. A "DTM" is commonly a bare-earth product, or one that is intended to provide a best representation of the terrain, and may incorporate ancillary information (i.e., breaklines) to better represent the surface. A "DSM" is a more loosely defined term and can include any type of product that represents a surface, whether bare earth or the surface along the tops of trees.

Most elevation applications are best served by bare-earth DEMs or DTMs. As shown earlier, this requires removal of points falling on non-terrain features (e.g., trees, cars, houses). This type of process is, for the most part, handled using lidar-specific software; however, there are some

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lidar-specific software extensions that work within ArcGIS that can be used to classify points and create a bare-earth DEM.

ArcGIS, with either 3D Analyst or Spatial Analyst, can interpolate DEMs from point data, and ArcGIS without any extensions can read and display several different DEM formats created with separate software. Analysis of the DEM (e.g., calculating height differences, generating aspect and slope grids, generating 3D profiles, or creating contours), however, requires one of the extensions.

As mentioned, ArcGIS can natively handle several gridded formats including GeoTiffs (.tif), Esri Grids, and ERDAS Imagine (.img) files. For other common formats, the "Conversion Tools" toolbox has most of the grid or raster import capabilities needed. The most commonly used for lidar data include the ASCII to Raster and Float (.flt) to Raster tools. When possible, it is advised that float or natively handled formats be used.

If any sort of analysis is planned, most users will need to have 3D Analyst or Spatial Analyst. Figures 4-14 and 4-15 were created in ArcGIS using 3D Analyst to first create a TIN (triangulated irregular network) data set and then convert to a grid (raster). The data were taken from a point data set that had been classified. The DSM (Figure 4-14) was created using all the points, and the DTM (Figure 4-15) was created by selecting only those with a classification of "2" (Figure 4-10), which is the standard class for ground points.
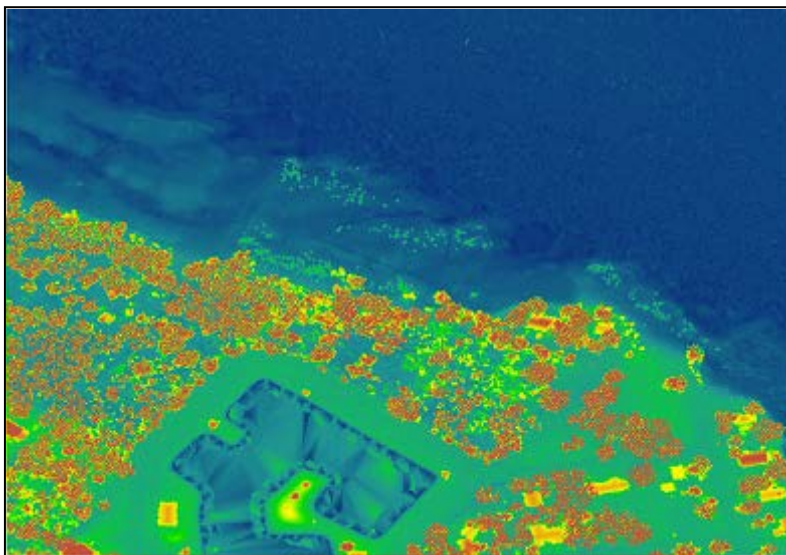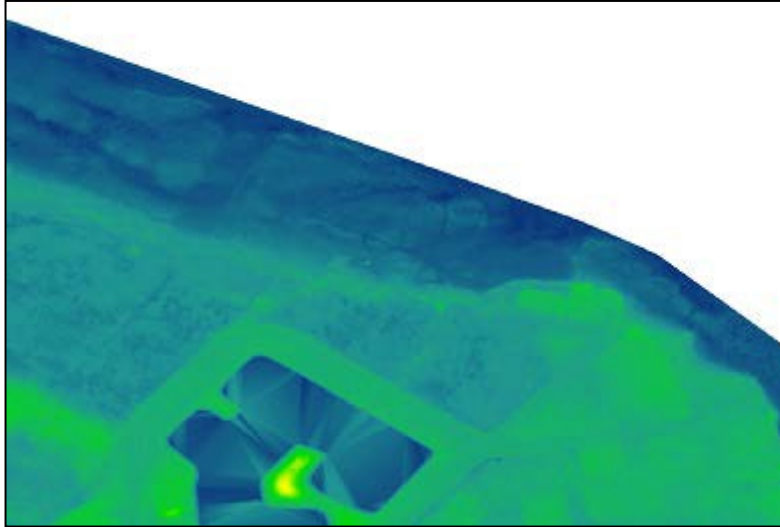

Figure 4-11. DSM

Figure 4-12. DTM or Bare-Earth DEM

Further "visualization" analysis of the surface in ArcGIS with the use of either 3D Analyst or Spatial Analyst may include creating a hillshade image (Figure 4-16). Hillshading brings out the more subtle aspects of the data and can help highlight smaller features and also flaws or collection aspects of the data. For example, the pattern of horizontal lines running at about 45 degrees in Figure 4-16 probably represents the scanning direction of the lidar sensor. The data have a "corn row" appearance and may be the result of a slight problem in the inertial measurement instrument (IMU). The corn rows are only a couple of centimeters but show up quite well—for better or worse. Contours made from these data will probably have a zig-zag appearance (especially in flatter areas). Hillshade rasters created in ArcGIS do not have "elevation" values; rather they are just black and white images.
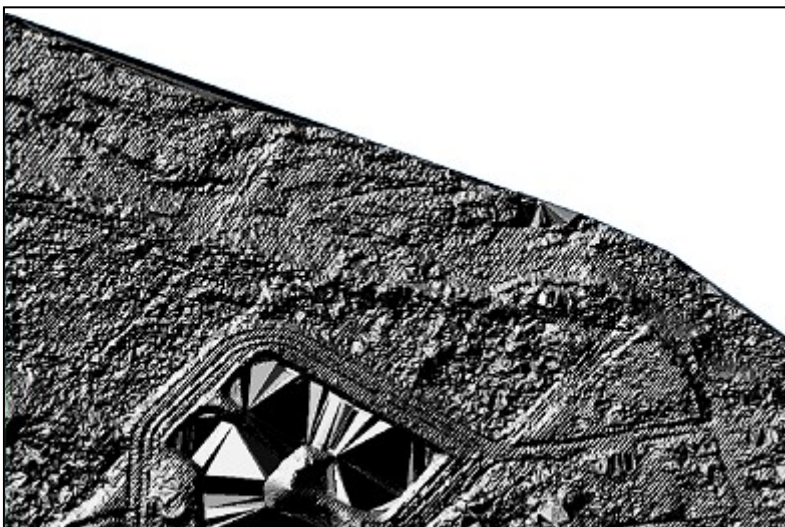

Figure 4-13. Hillshade

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Hillshade layers can, however, be made semi-transparent and be draped over the elevation data to create a "composite" DEM (Figure 4-17). In addition, composite hillshaded images can also be created by draping orthoimages over an elevation grid (Figure 4-18).
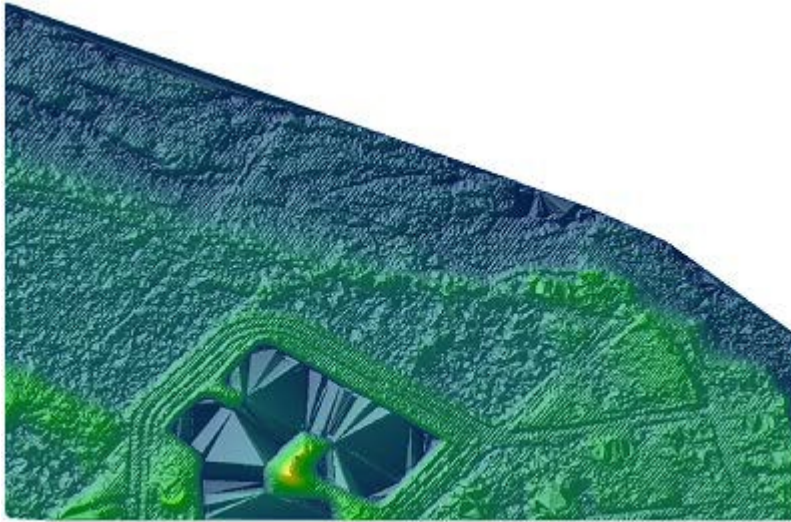
Figure 4-14. Hillshaded, Color-Ramped DEM
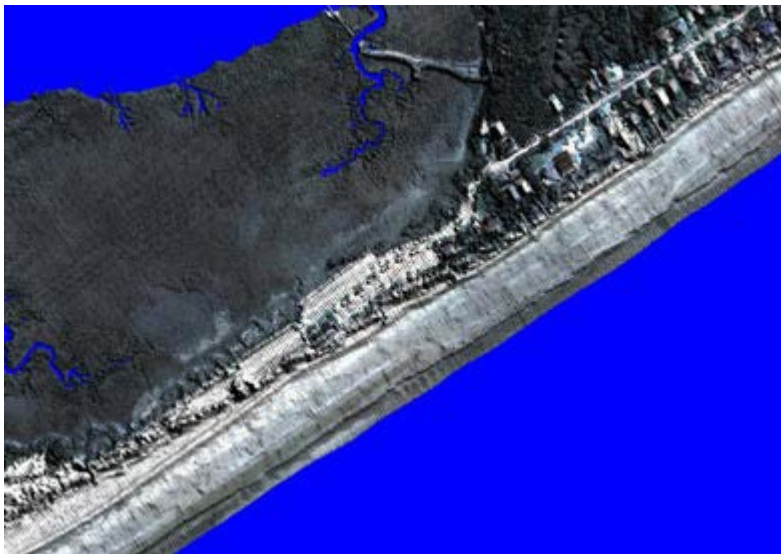
Figure 4-15. Hillshaded Image

Finally, a common analysis of a surface is generation of contours (Figure 4-19), which could include generation of a shoreline (e.g., an elevation representing mean high water or mean sea level). As mentioned before, contours generated from lidar data will not typically have a smooth appearance, even if using only bare earth, since the data contain significant high frequency "noise" (i.e., lots of closely spaced points with slightly varying elevation values).

Contours can be generated using either 3D Analyst or Spatial Analyst (Surface > Contour). While contours are a popular product, it should be noted that much of the data is being lost and that contours are a "simplification" technique.

Figure 4-19. Contours overlain on bare-earth surface

These are examples of some simple "visualization" techniques that can benefit most applications; further analysis will depend largely on the specific use or application of the data. Three-dimensional visualization is rapidly becoming more common and does bring a more intuitive aspect to the data.
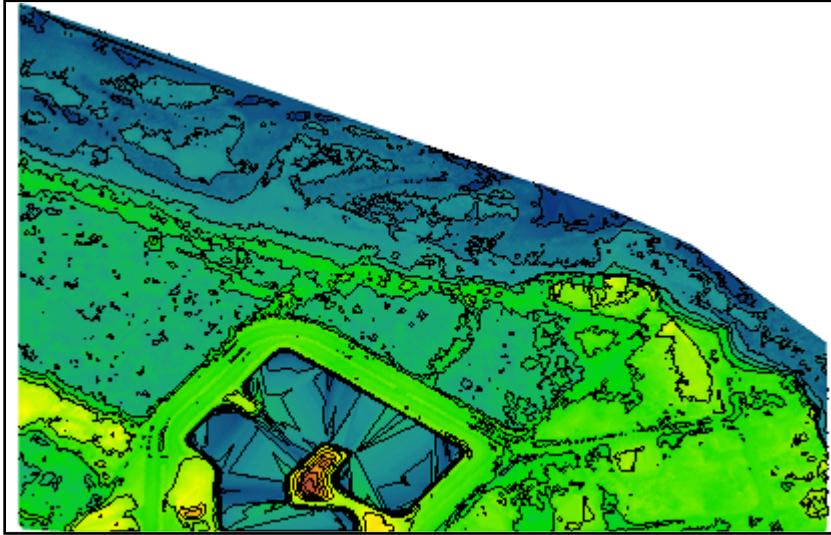
Metadata

Metadata are integral for maximizing the use of lidar data, since metadata typically provide the collection parameters, accuracy, and contacts for further information, which may include full collection and quality control reports. The primary aspects of metadata are similar to other data and include the description, data quality, spatial reference information, and contacts. It answers the "what," "where," "when," and "how good" questions. It is important to keep in mind that lidar is generally collected over small project sizes and can be collected at multiple times; thus, keeping track of data set variables is important if working on an area that overlaps several data sets. Metadata provide this information, including contacts that are best suited to answer data questions not covered. For example, if a noticeable offset between two lidar data sets occurs, the metadata will help determine what steps should be taken to fix the problem or who could provide additional insight. Even when fully compliant metadata are available, there are aspects that may not be covered and can only be determined through points of contact.

Summary

Using lidar data in some GIS programs does have inherent difficulties that stem from the large amount of data that is provided for even small areas. Points can be loaded in several formats;

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however, the sheer number of them can create usage problems. A simple solution is to get the data as a pre-made DEM (raster) or as contours (lines); both are generally easier to use than the raw points. If custom surfaces are desired, the points can be used to create surfaces in some programs or with additional extensions in ArcGIS. Once surfaces are created, different analyses can be performed for both visualization and analytic purposes. To maximize the use of the analyses and operate within the data set's limits, it is important to examine the metadata for the accuracy and, also, the processes used to generate the raw data. This chapter highlighted Esri's ArcGIS platform and associated methods given its widespread use within the coastal management community.

5. Data Customization and Specification

Overview

Certain user or customer specifications can help maximize the data for specific applications. Lidar data, like most remote sensing information, can be highly customized to satisfy a certain use. The downside, however, is that there can be a host of "options" to wade through, both in use and in purchasing. This chapter focuses on two attributes of lidar point data that are user-selectable and directly influence the form and representation of derived elevation products such as DEMs and contours. These attributes are discussed in the context of the standard LAS format used for lidar point clouds. The chapter goes on to describe the use of breaklines in refining lidar products. There is a thorough discussion of data accuracy and consistency, because the most important option when purchasing lidar data, and often the primary cost driver, is the accuracy requirement. The chapter concludes with an exploration of user-selectable options in NOAA's Digital Coast Data Access Viewer and considerations for those who seek to obtain lidar data from this source.

Data Attributes

Several references to classified data have been made in the earlier sections of this guide; classification is an example of an important attribute in the data set. Use of data attributes requires an understanding of what they are and, to some degree, where they reside in the file. The most common lidar point cloud file format is the LAS format (ASPRS, 2009). There are two primary "sections" of an LAS file: the header and the data. The header is accessible using most lidar software, including free software. The information in Box 1 is an example of the first portion of the header where file information is stored. Box 2 is an example of additional header information, including georeferencing information that may be provided as variable length records that follow the primary header information.

```
Statistics
 ----------
 Horizontal Mean:         2.81
 Biased Horizontal Mean:  2.75
 Biased Point Density :   3.31
 Source ID Count :    4
LAS Header
 ----------
 GUID:                    00000000-0000-0000-0000-
000000000000
 LAS Version:             1.0
 System ID:               <empty>
 Generating Software:     TerraScan
 Flight Date Julian:      0
 Year:                    0

 Header Size:             227
 Point Data Offset:       709
 VLR Count:               5

 Point Data Format:       Format 1
 Point Data Record Length: 28
 Number of Point Records:  3133353
 Points By Return
                Return 1: 2435079
                Return 2: 582099
                Return 3: 109295
                Return 4: 6880
                Return 5: 0

 X,Y,Z Scale Factors:     0.0100, 0.0100, 0.0010
 X,Y,Z Offsets:           0.00, 0.00, 0.00
 Min, Max X:              2259257.54, 2264183.12
 Min, Max Y:              351365.95, 356291.85
```

Box 1. Main portion of LAS file header

```
VARIABLE RECORD:
user ID: LASF_Projection
record ID: 34735
record data length: 48
description: Projection Parameters
GeoKey:
        Directory Version = 1
        Revision = 1
        MinorRevision = 0
        Number of Keys = 5
        Key = 1024 (GTModelTypeGeoKey)
                Value = 1 (ModelTypeProjected)
        Key = 3072 (ProjectedCSTypeGeoKey)
                Value = 32133
 (PCS_NAD83_South_Carolina)
        Key = 3076 (ProjLinearUnitsGeoKey)
                Value = 9002 (Linear_Foot)
        Key = 4096 (VerticalCSTypeGeoKey)
                 Value = 5103
 (VertCS_North_American_Vertical_Datum_1988)
```

Box 2. Variable records in the LAS header

Following the header and variable length records are the data. The data are in binary format (as is the entire file), which cannot be read with most text editors. Below is an example of three point records contained in a LAS file, with attributes and their values. In some cases, the

originating lidar system may not generate data for all the fields; for example, scan angle is primarily applicable to oscillating mirror systems.

```
x=230848811, y=33168639, z=4690, i=255, ret#=1, #rets=1, scandir=1, edge=0, class=2,
angle=2, user_data=130, pt_src_id=417, gps_time=427007.220038

x=230849349, y=33168619, z=16796, i=99, ret#=1, #rets=2, scandir=0, edge=0, class=1,
angle=2, user_data=123, pt_src_id=417, gps_time=427007.230120

x=230848993, y=33168525, z=4788, i=175, ret#=1, #rets=1, scandir=0, edge=0, class=2,
angle=2, user_data=122, pt_src_id=417, gps_time=427007.230133
```

Note that there are no decimal numbers in the x,y,z portion of the data. The decimal portions are handled in the header—in the "X,Y,Z Scale Factors" line, which in this case is 0.0100, 0.0100, 0.0010. Return number (ret #) and number of returns (#ret) provide relative information on how many "objects" the laser pulse hit (Figure 5-1) and which hit the value is from. The "scandir" field describes which way the scan mirror was moving (left or right). The "edge" value represents the last point in the scan direction (i.e., last point before the scan mirror turns around and goes the other way). "Class" refers to the points classification (see below); "angle" was discussed above. "User data" is an open field that can be used by the lidar vendor for its use. "Pt_src_id" is typically the flight line and "gps_time" is the time the point was collected.

Return Numbers

Along with higher pulse rates, the ability to discern multiple returns is a major advance in lidar technology (Figure 5-1). Early lidar systems provided single or first and last returns only, but contemporary systems are capable of providing at least three returns per pulse. The return number and its order (i.e., 1 of 2, 1 of 1, 2 of 4) provide important information for follow-on classifications; for example, any middle returns are very unlikely to be ground and multiple returns typically will be in vegetation—not on structures.

Figure 5-1. Multiple returns from single laser pulse

The following figures (Figures 5-2 to 5-4) highlight the different types of surfaces that multiple returns can produce. A surface developed from all returns (Figure 5-2) is "noisy" because, depending on the binning and interpolation methods used, it may include returns from the ground, mid-canopy, and top-of-canopy. A surface created only from "last returns" produces a slightly smoother surface (Figure 5-3) but still contains points falling on buildings and dense trees and vegetation; last-return data should not be confused with bare-earth data. Using only the last of multiple returns
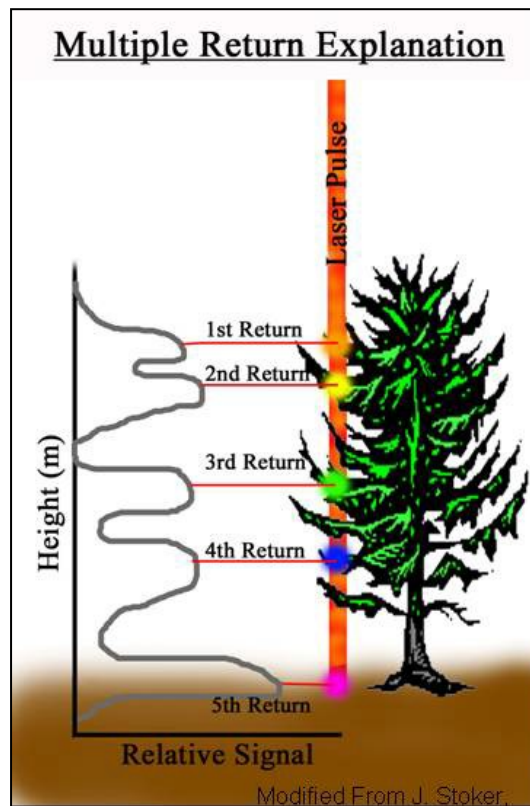
(Figure 5-4) removes nearly all structures, except ones under trees, and most vegetation, although some lower-lying vegetation remains. It also removes bare-earth points from open areas. None of these examples provides a bare-earth product; however, the "last-return only" surface produces the closest approximation, although it misses a significant amount of information.
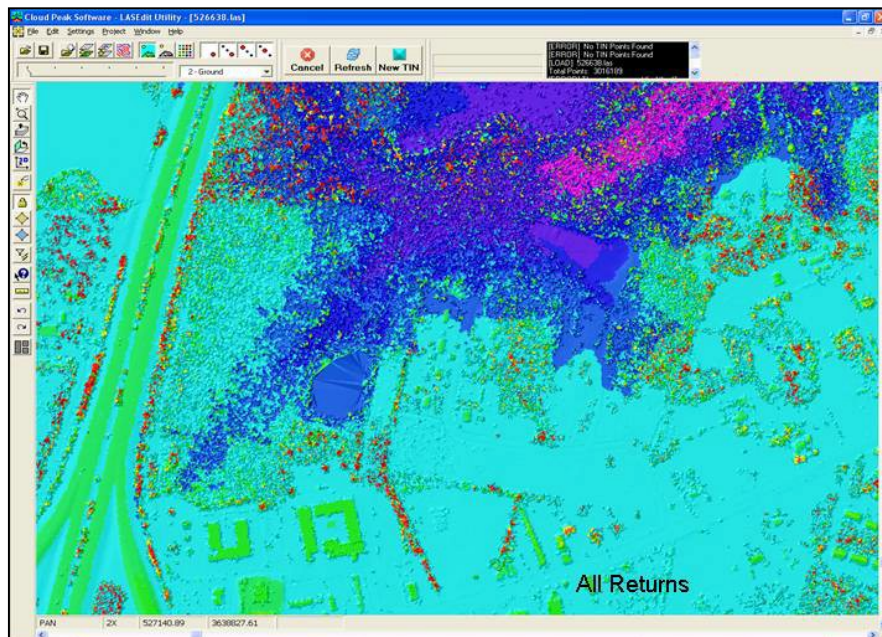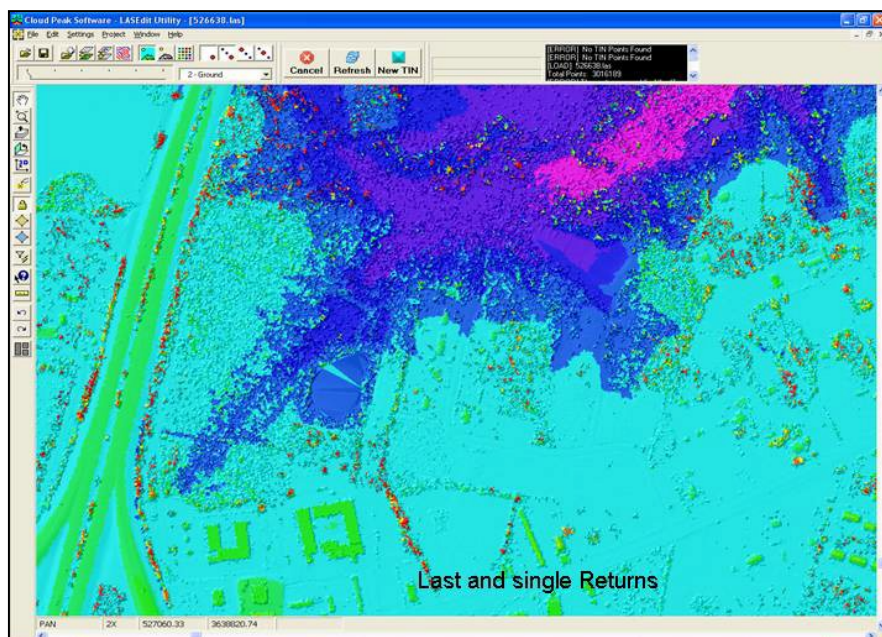

Figure 5-1. All- returns DEM

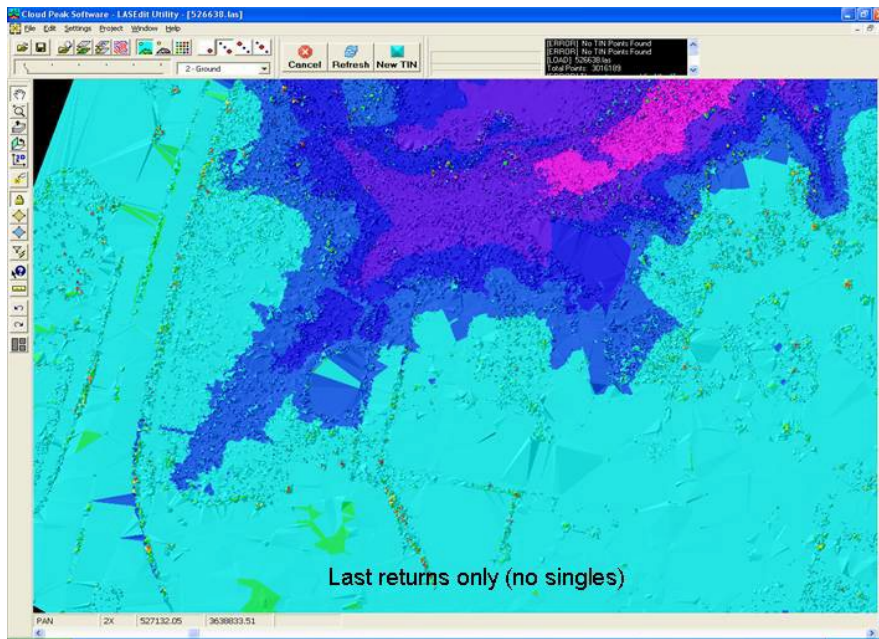**Figure 5-2. Single (1 of 1) and last-returns (2 of 2, 3 of 3) DEM**

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Figure 5-3. Last-return DEM – only those points that were last of two or more (e.g., 2 of 2, 3 of 3)

Figure 5-4. Bare-earth DEM

Classification
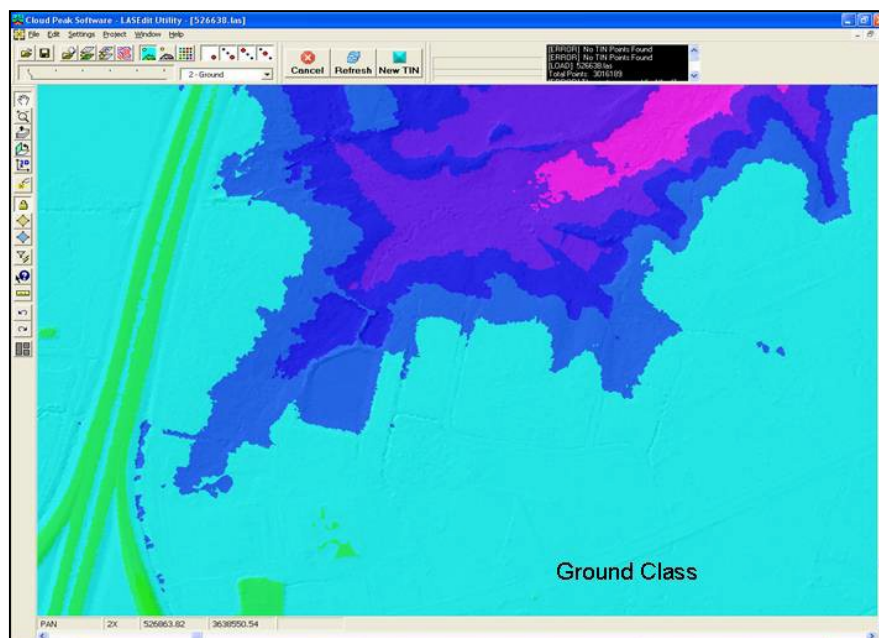
Editing lidar point data to improve final DEM accuracy and usability is usually conducted within the LAS data workflow. Production of classified data models allows all the original points to be retained while affording the user flexibility to select specific classes of points for final surface generation. Classification of lidar data is usually undertaken to produce a point set that

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represents only the returns that hit the "bare ground" (Figure 5-5). The remaining points are typically moved to an "unclassified" class. When creating a DEM, it is then possible to remove all "extraneous" points to create the best possible representation of a bare-earth surface (Figure 5-5). This represents the simplest classification case; more specification can be accomplished, and classification of features (e.g., trees, houses) is becoming a common trend.

There is an American Society for Photogrammetry and Remote Sensing (ASPRS) classification scheme that is used by most lidar producers (Box 3). The primary values are 1, 2, and 9. Water is an especially important consideration for coastal areas, since the water is essentially flat and can often be classified as "ground" in automated processes (Figure 5-6); this can hold true for ponds and other water bodies as well.

```
Classification Value and Meaning
0 Created, never classified
1 Unclassified
2 Ground
3 Low Vegetation
4 Medium Vegetation
5 High Vegetation
6 Building
7 Low Point (noise)
8 Model Key-point (mass point)
9 Water
10 Reserved for ASPRS Definition
11 Reserved for ASPRS Definition
12 Overlap Points
13-31 Reserved for ASPRS Definition
```

Box 3. ASPRS classification values
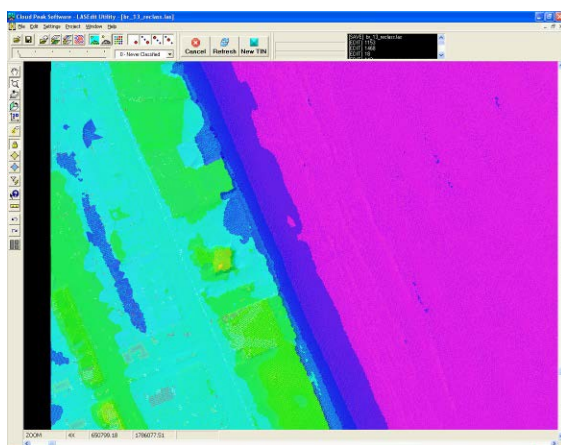
A. Water classified as "Bare- Earth"   **B. Water classified as "Water"**
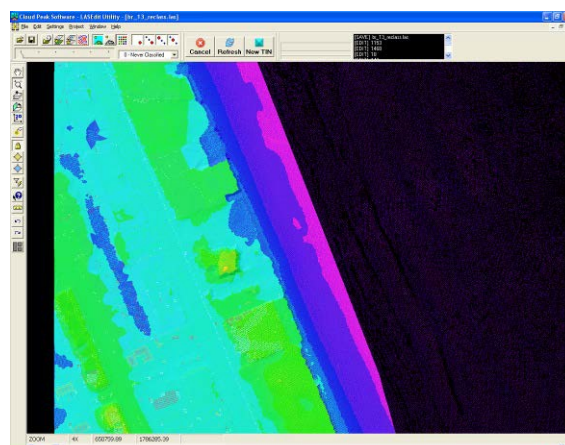
Figure 5-5. Images Depicting Differences in Distribution of Points Classified asWater

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More and more, the use of classifications is expanding to include differentiation between vegetation and structures or between tall and short vegetation (Figure 5-7). From these classifications, hybrid or customized DEMs can be produced to represent built infrastructure or vegetation models. Additionally, the data can be used in characterizing different types of land cover; for example, the average or maximum heights of vegetation for a specific area can be compared to other areas or the entire data set.
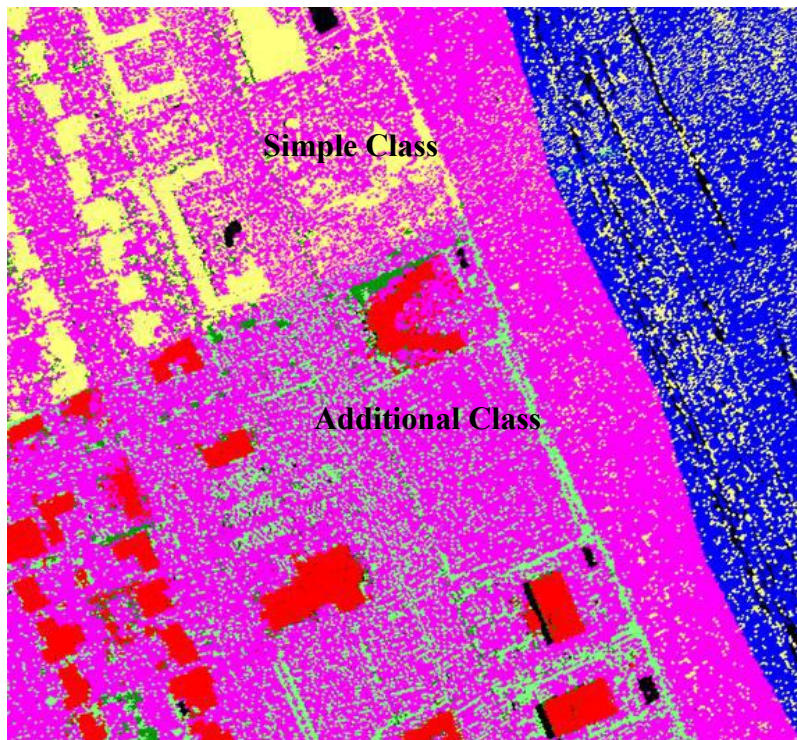

Figure 5-6. Lidar points with two different classification schemes. The top portion is simpler than the Lower, which has buildings and different vegetation heights classified.

Breaklines

Point classification and filtration greatly improve the final representation of terrain, but additional editing and information is required to produce hydrologically and cartographically correct DEMs. This is typically done through the introduction of three-dimensional breaklines. Breaklines are features that represent significant breaks in slope or that delineate edges of features such as rivers, bays, and other water bodies. One of the most common uses of breaklines is in the process of hydrologic correction in DEMS.

There are several types of hydrologic correction, including hydrologic enforcement and flattening; hydrologic enforcement creates a network of water bodies with a general down-slope flow, hydrologic flattening creates a more pleasing appearance to the DEM by making water bodies flat. These processes are performed because 1) lidar returns from water surfaces are neither consistent nor accurate and therefore shouldn't necessarily be used to define water

surface elevations or boundaries; 2) lidar collections are not always timed to acquire data at specific tide stages or water levels; and 3) ultimately because it is important that hydrologic features be represented accurately to facilitate successful hydraulic and hydrologic modeling activities.

At a national level, the USGS National Geospatial Program requires that all the DEMs in the National Elevation Dataset (NED) have their inland and coastal water bodies flattened. Breaklines are used in the DEM development process to accomplish this. In flattened DEMs, breakline values are typically set at the lowest ground point in lakes and using gradients in rivers that preserve bank elevations at their measured elevation. Coastal values are typically chosen at a value that maintains as much data as possible. In some cases the bare-earth lidar points (Class 2) directly adjacent to the breaklines are reclassified to "Ignored Ground" (class value = 10) and excluded during surface generation. This produces a smoother transition from upland to the shoreline.

Lidar systems and processing algorithms do not inherently collect breaklines required for hydro-flattening. However, they can be generated separately through a variety of techniques using the lidar points or ancillary data. In cases where breaklines are used in DEM development, they are typically delivered as PolylineZ or PolygonZ Esri feature classes (either in shapefile or geodatabase formats). The Lidar Processing report that accompanies these lidar data deliverables should also include a description of the method used for breakline collection.

Accuracy Specification and Tests

As mentioned in the previous section, the accuracy specification is an important piece of information and is commonly found in the metadata. In addition, most data sets also have an accompanying report on the collection parameters and data quality (Table 5-1). The most common way to express accuracy is through the root mean square error (RMSE). The RMSE is analogous to the standard deviation of a non-biased data set (i.e., a data set that has errors equally distributed above and below zero), such that about 68% of the data would fall within the range of the RMSE or 1 standard deviation. The other term that is common is $Accuracy_z$. This generally equates to 2 standard deviations (with non-biased data), such that 95% of the data falls within the $Accuracy_z$ value. For example, a data set with an $Accuracy_z$ of 25 centimeters should have 95% of the data fall within 25 centimeters of their true value.

As described in chapter 3, the accuracy values are calculated using ground control points (GCP) that have been surveyed throughout the collection areas and have accurate elevation values. The lidar data are used to create a TIN surface that is compared to the GCP point data. A TIN surface is used because there is very little chance that the GCP points will exactly coincide with the lidar data points, and a TIN is a simple, non-biased method for interpolating a value from the nearest points.

In most cases, a minimum of 20 GCP points are collected per land cover category. This allows one point to fail the vertical accuracy specification without causing the entire dataset to fail the 95% confidence limit. An example of the analysis is presented in Table 5-1 and Figure 5-8, with separate accuracy values and population graphs calculated for bare earth, forested, scrub/shrub, weeds and crops, and urban areas. Note that in this case there were 166 points.

Table 5-1. Accuracy Summary of Lidar Data Set

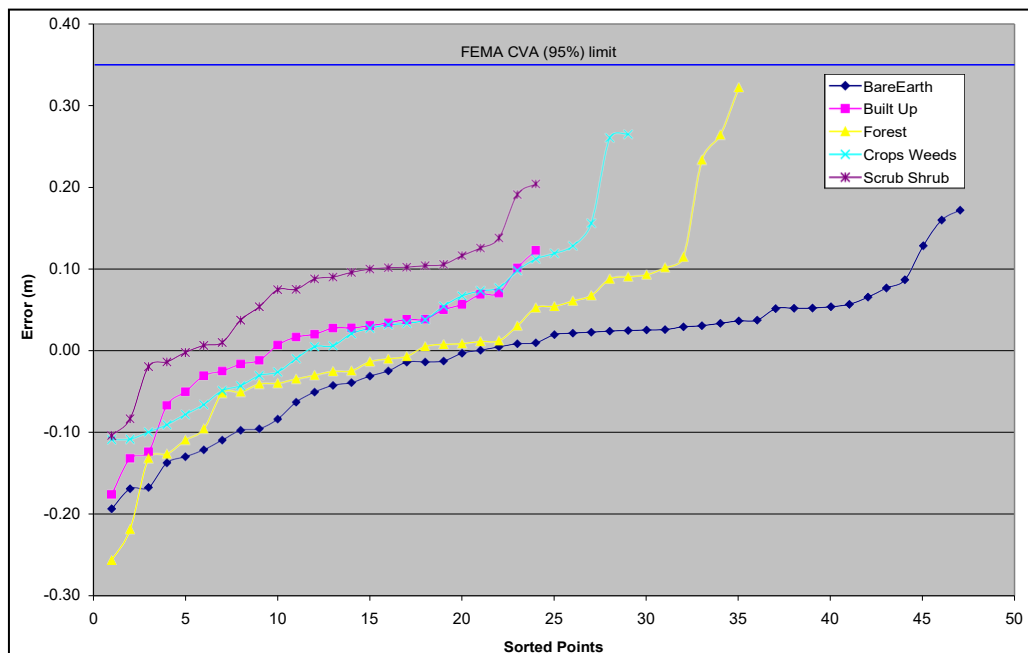| Land Cover Type	No. of Points	RMSE (cm)	Accuracy$_z$ or FVA (1.96 x RMSE) (cm)	Consolidated Vertical Accuracy, CVA (95th percentile) (cm)	Supplemental Vertical Accuracy, SVA (95th percentile) (cm)
Total Combined (all points)	166	0.094	0.19	**0.19**	
Open Terrain	47	0.081	**0.16**		0.12
Weeds/Crops	36	0.098	0.19		0.18
Scrub/Shrub	24	0.100	0.20		0.18
Forest	35	0.116	0.23		0.26
Built-up/Urban	24	0.071	0.14		0.13

Figure 5-7. Lidar errors at ground control points with points sorted by error

The basic premise is that the "bare-earth" points represent the best possible accuracy of the system and the collection parameters. The accuracies in the other land covers generally relate to how well the processing was done to remove vegetation and structures from bare-earth points. The urban or built category is also tested separately because very dark and very bright surfaces (e.g., roads) absorb or reflect laser pulses in ways that introduce inaccuracies in these areas.

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Use of the data for specific applications may depend on the accuracy of the data for specific land covers. For example, shoreline delineation requires only a high level of accuracy in the bare-earth category (FVA), whereas flood mapping requires that both bare earth and forested areas have accuracies suitable for creating a specific contour interval (CVA). If a data set has good bare-earth accuracy but was poorly classified for vegetation, then it may not be usable for flood mapping; however, the data set will still work well for shoreline delineation.

High accuracy comes at a price and should be specified based on the needs of the project or likely uses. When considering "likely uses," it is probable that future uses will benefit from higher accuracies, so it is generally better to ask for higher accuracies to increase the shelf life of the data set.

Qualitative Review of Lidar Data

Unlike the clearly defined accuracy requirements, the qualitative aspect of the data is a bit more subjective. While, it does not commonly receive the same amount of attention on the front end, it is a critical check for the successful use of the data. In essence, the accuracy assessment tests only 200 to 300 points in a data set of a billion points, so the qualitative review can be seen as a test of the other billion or so points. There are, however, no specified qualitative accuracy procedures, so familiarity with lidar data in general and the location and intended use in particular are typically necessary. Since it is a "fuzzy" analysis, it is generally best to have it performed by a third party, the purchaser, or a user group.

Some of the most common qualitative "errors" are flightline mismatches where points from adjacent flightlines do not match and generate the appearance of a systematic offset (Figure 5-9), high frequency noise—also called "corn rows" (Figure 5-10), formatting (Figure 5-11), misclassification (Figure 5-12), and data holidays or voids (Figure 5-13). While many of these problems can be fixed, corn rows are more difficult to remedy. It should be mentioned that there are no "perfect" data sets, but there is generally a level at which the data set loses some of its usability; that threshold should be considered when specifying the data.
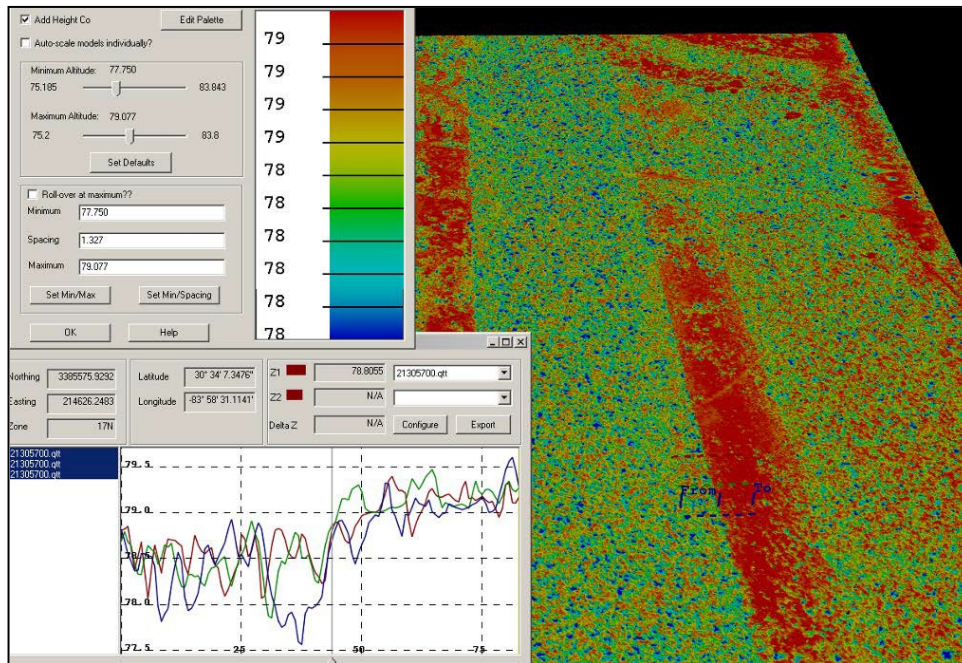
Figure 5-8. Flightline mismatch evident as linear features in colored graphic (courtesy Dewberry)
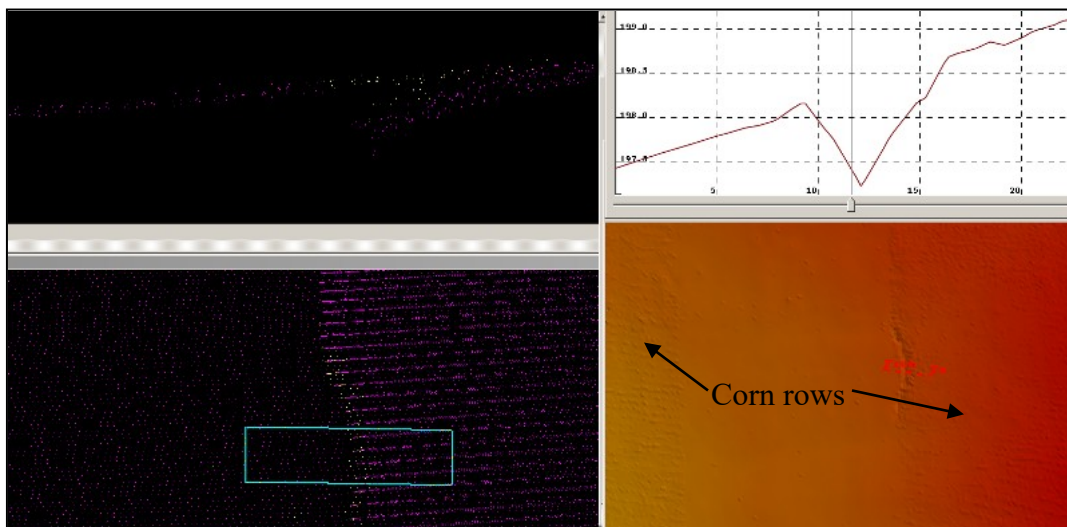

Figure 5-9. Corn rows evident as parallel ridges (courtesy Dewberry)
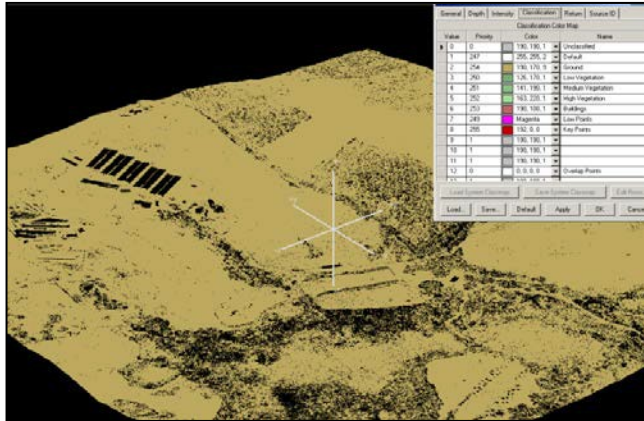
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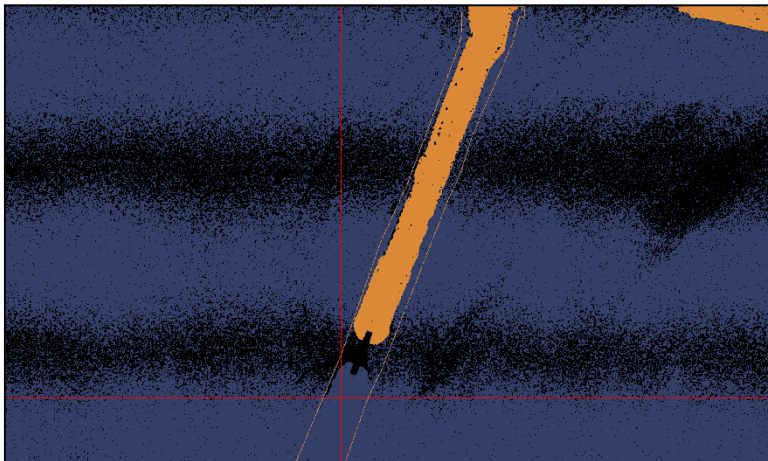**Figure 5-10. Format issue – only bare-earth points in the file (courtesy Dewberry)**

Figure 5-11. Misclassification of earthen roadway (bottom-center in crosshairs) across water body (blue is water, brown is land)
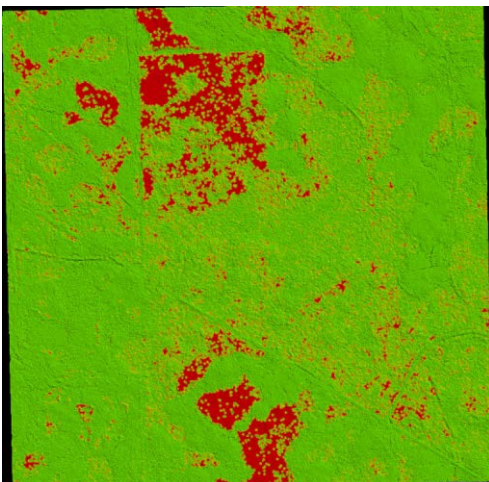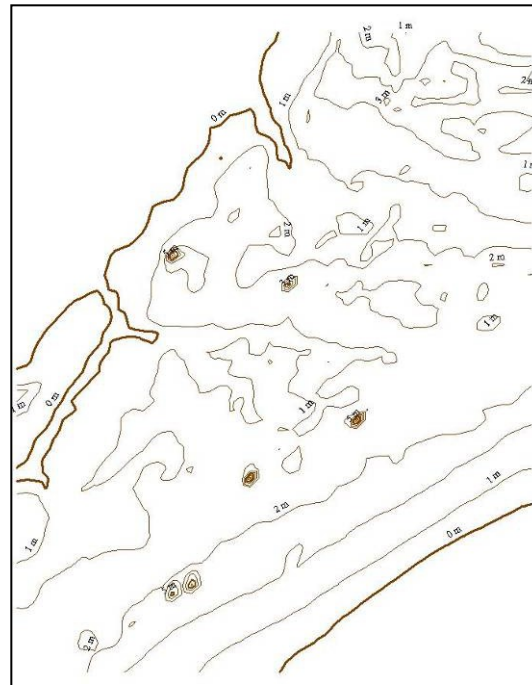

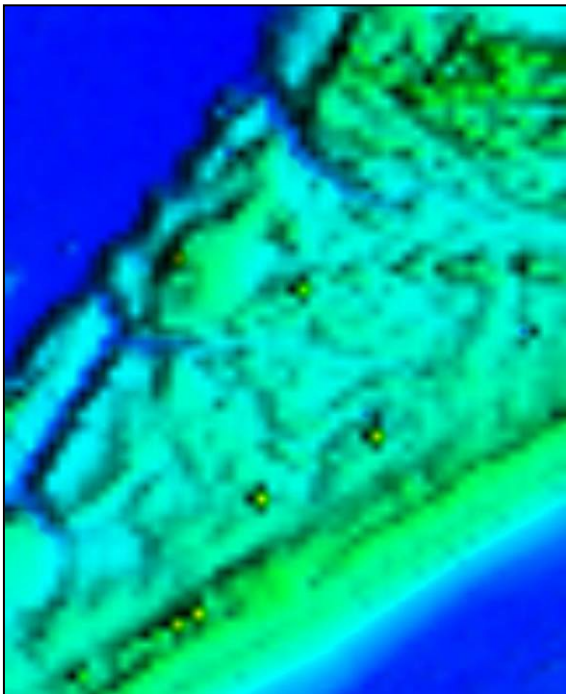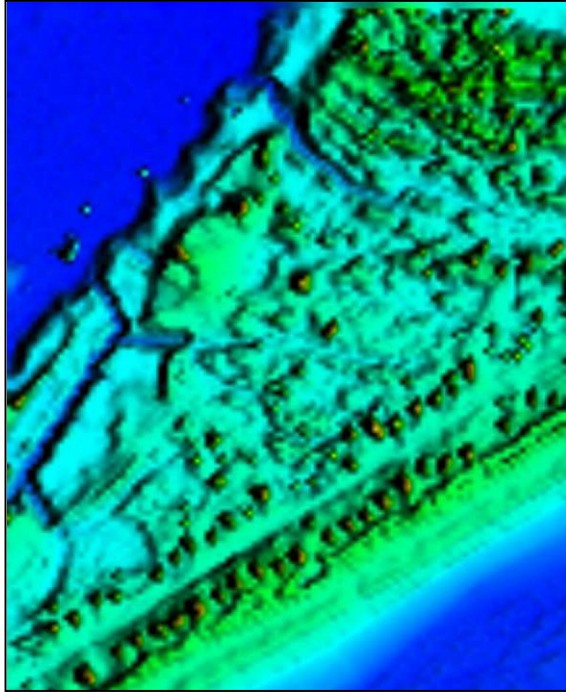**Figure 5-12. Data "holes" (red = no points) in data (courtesy Dewberry)**
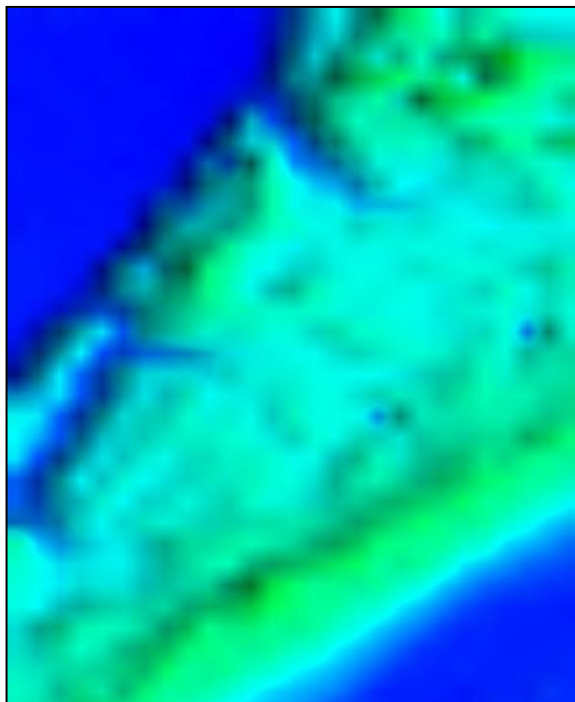
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Data Attribute Specification in Digital Coast

While there are many sites for downloading data, the Digital Coast Data Access Viewer provides the ability to specify data classifications (for data that have been processed for bare earth) and returns (for data with more than single returns) when provisioning the data (NOAA, 2011). This information is also available when requesting LAS files, although with a LAS file it is generally better to get all the data and do the point selection on the user side (i.e., turn off non-ground points if the software being used can perform this function).
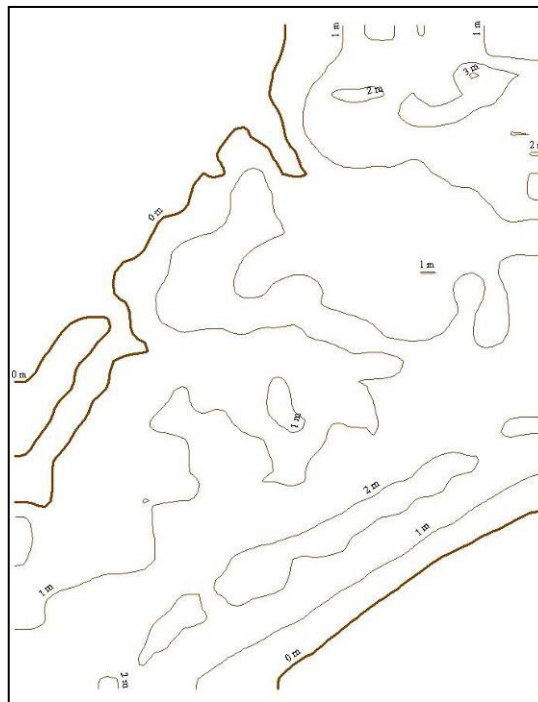
When the data have not been classified, but bare earth is sought, the bin method, cell size, and returns values can be specified to decrease the number of non-ground points. Use of the "minimum" bin option in the specification along with a larger cell size helps remove vegetation and other non-ground features such as houses, and if contours are being sought the smoothing may be preferable to higher resolution spikes. However, there comes a point when the smoothing results in a diminished return. The gains in feature removal are offset by loss in resolution, and the level where any advantage is gained will largely depend on the intended use.

As an example, several iterations of data sets were created by progressively increasing grid cell sizes and selecting the minimum points in each cell (Figure 5-14). At a 5-meter cell size, all the coastal features, houses, and vegetation largely remain and the data provide a significant level of detail. Expanding the cell size to 10 meters removes many of the houses, although some remain, and begins to remove some tall vegetation (top right corner). At 10 meters many of the subtle land features are still present, providing a fair amount of detail. Expanding to a 20-meter cell size removes all the houses, and bare-earth surface is essentially all that remains. There is, however, a significant loss of detail in that subtle features such as the dune are largely removed—and the overall elevation is likely a bit low since small depressions within a cell become the cell's overall value. Using this iterative approach, a 15-meter cell size may prove to be the most appropriate for removing structures and trees while maintaining a level of accuracy and enough topographic information for many environmental and habitat applications.

A. 5-meter grid with minimum value

B. Contours generated from 5-meter grid

C. 10-meter grid with minimum value

D. Contours generated from 10-meter grid

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E. 20-Meter grid with minimum value   **F. Contours generated from 20-meter grid**

Figure 5-13. Various grid sizes with minimum values

There are other specification variations in Digital Coast that can be employed to maximize the information for specific uses; the previous example is, however, one of the more common. Fortunately, newer data sets are being produced with a wider audience in mind so that the data are more user-friendly (i.e., bare earth has been classified so that features can be extracted more easily) and can be used for many different applications and analyses.

Summary

Lidar data are evolving from simple x,y,z points to classified data sets with unique attributes and classification schemes. The LAS format is designed to handle the common attributes, data parameters, and classifications while still maximizing data storage efficiency. Noting or defining the data quality is paramount when acquiring or downloading lidar data; the level of data quality is a major cost driver. Accuracy assessments provide important information for defining specific data use. Qualitative assessments provide a broad check of the data's overall use. Classifications, most often used to define bare-earth products, are increasingly being used to define features. In data sets where classifications are absent, some selection (last returns) and resampling (increasing grid sizes) can be performed to begin approximating a bare-earth product. The USGS's *Base Lidar Specification – Version 13* (USGS NGP, 2010) is a valuable resource for organizations interested in purchasing airborne lidar data. The document contains base specifications (i.e., minimum parameters) and recommendations for lidar acquisitions to help ensure consistency among lidar data sets and improve data utility.

6. Examples of Coastal Lidar Applications

Overview

The results of an analysis can vary when using the same base data if different processing techniques are used; this is both an advantage and a disadvantage to the use of lidar data. This variance stems from the massive amount of data and the need to resample or group them (i.e., grid them). On the positive side, a significant amount of data can be removed to get only the information sought; on the negative side, the techniques used to sample the data will or could vary and create incompatible results. Some examples are provided to show how data can be specified to maximize a specific use and also how this may create variability within one data set.

Shoreline Mapping

Lidar coverage is expanding rapidly along the U.S. shoreline, and as a result lidar data are increasingly being used for shoreline mapping, including defining shoreline positions and quantifying rates of shoreline change. Shoreline—and its many tidal datum variations—is commonly referenced as a boundary component in legal descriptions, as the point of origin for jurisdictional boundaries, and as the boundary between public and private ownership (Figure 6-1). These various definitions of shorelines are based on water levels that are influenced by tides and currents.
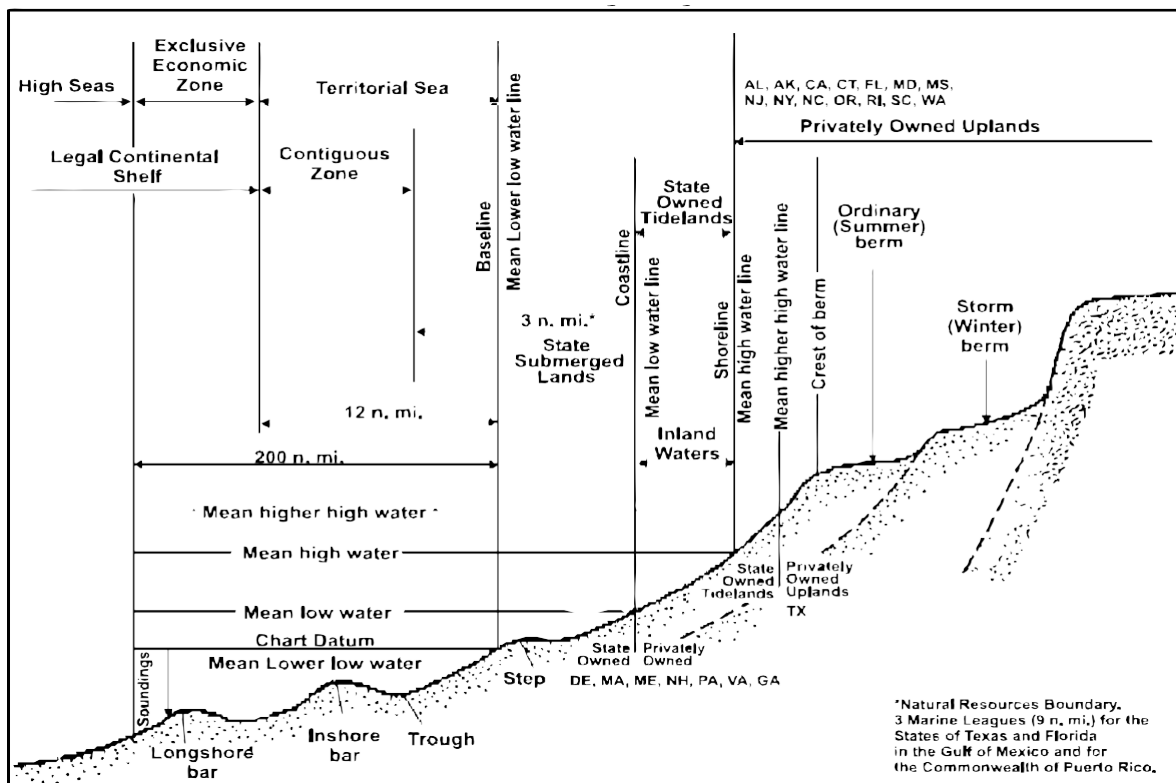

Figure 6-1. Legal significance of shoreline where the intersection of the tidal datum with land determines the landward edge of a marine boundary (Gill and Schultz, 2001; reprinted courtesy of NOAA)

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The different shorelines shown above have traditionally been inferred from various indicators or proxies such as vegetation lines, dune lines, beach scarps, wet–dry lines, and more (White and others, 2011). Long-term water level records have led to the development of datum-based shorelines that rely on known relationships between tidal, orthometric, and ellipsoidal vertical datums.

Changes in shorelines through processes of accretion and erosion can be analyzed by measuring differences in past and present shoreline locations (Figure 6-2). This information is used to quantify erosion rates and adjust setback regulations.

Figure 6-2. Shorelines migrate over time, through processes of erosion and accretion

NOAA's National Geodetic Survey, or NGS, started testing lidar data to map shorelines in 2000 and incorporated a lidar-derived shoreline in a chart for the first time in 2004. One of the main benefits of using lidar to map shorelines is that tide-coordination requirements are not as stringent as with the traditional photogrammetric procedures: it is typically only necessary to collect data below a certain tide stage, rather than within a narrow tide window (White and others, 2011). Topographic lidar provides multiple elevation readings per square meter but cannot penetrate the water surface (due to the laser's wavelength). This results in a very densely sampled "dry" area on most coastlines but a lack of information seaward of water's edge at the time of acquisition. Bathymetric lidar can, with a different wavelength, penetrate the water surface and provide depth or "bathy" information out to about 70 meters in clear water. In areas with highly turbid waters or breaking waves, however, the penetration depth is

on the order of feet or less. For most shoreline extraction and coastal science applications, it is more important to have high-resolution, seamless data across the backshore, intertidal, and shallow nearshore zones. There are several combined topographic and bathymetric lidar systems that have been used extensively to map shoreline and nearshore areas. Combined topographic-bathymetric lidar data sets, such as those collected by the Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX), provide the critical elevation data required to produce datum-based shorelines. However, the spacing for bathymetric points is fairly wide compared to the tight spacing of topographic points, and there are often large gaps in areas with significant wave action and high turbidity (Figure 6-3). It is thus often preferable to derive shorelines using topographic lidar that was collected at a low tide stage (e.g., mean lower low water (MLLW)). Collecting it at a low tide stage permits higher shorelines to be mapped using a single data set (e.g., mean sea level (MSL), mean high water (MHW)). However, in practice, it is extremely challenging to map MLLW from topo-only lidar data. This is because it is operationally challenging in many project sites to acquire the data at a sufficiently low tide stage that the MLLW line is exposed (i.e., above water) throughout the project site. Furthermore, the data in the vicinity of the MLLW shoreline are often sparse and noisy, due to low backscatter from wet surfaces when operating at near-infrared wavelengths. And finally, many algorithms are unstable near the edges of coverage in a data set. These challenges are best overcome with seamless topo-bathy data generated from systems configured for such environments, though using these systems does not guarantee good, continuous coverage across the land-water interface (Parrish, 2012).
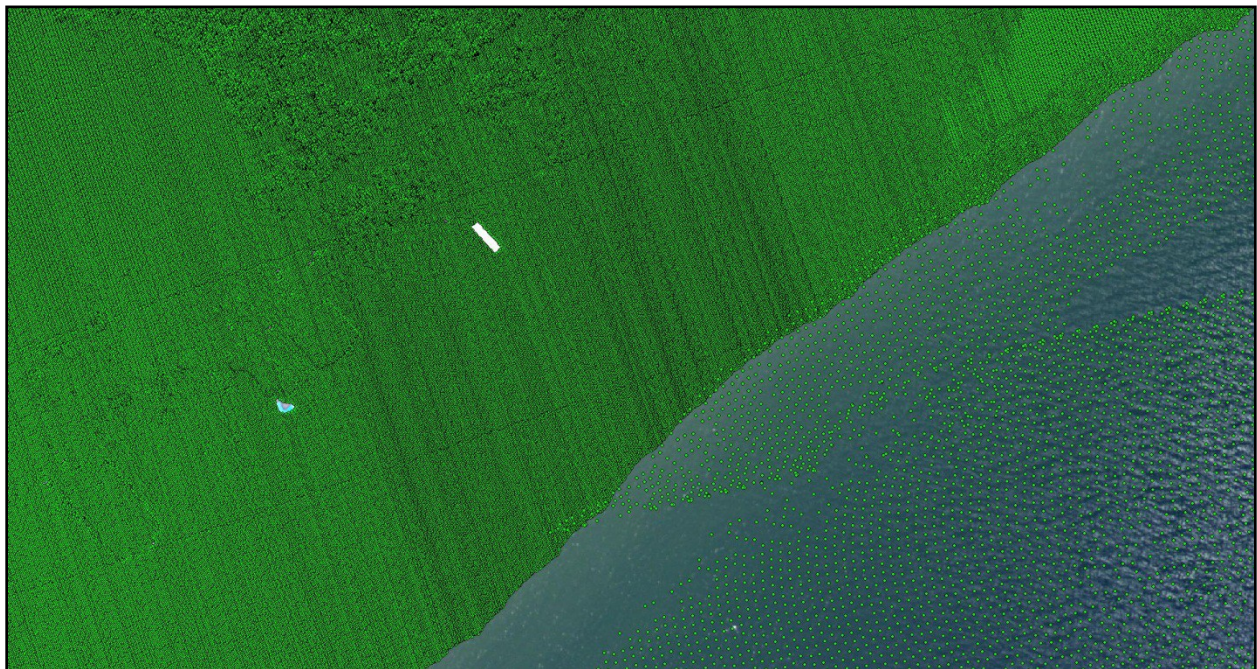

Figure 6-3. Topographic (high density) and bathymetric (low density) lidar points displayed on an aerial image

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For the purposes of mapping a specific shoreline (e.g., MLLW, MHW), lidar-based procedures help eliminate some of the subjectivity and interpretation biases common with photogrammetric techniques (Espy, 2003; White and others, 2011). Once a base DEM has been created from the lidar points, different users can take the information and create a repeatable shoreline based on a specific elevation; this is the advantage of a complete digital coastal elevation model (Guenther, 2007). There are many ways to create a DEM from lidar data. In some cases the user has control over the types of routines or methods used to generate the DEM, and in other cases, the user is provided with a pre-made DEM. NOAA's NGS published its lidar-based shoreline mapping workflow in White and others (2011). The workflow begins with lidar point data (which were collected using strict requirements) that are processed and ultimately converted to a gridded DEM (Figure 6-4). The use of NOAA's VDatum tool is a critical component of this workflow, as it makes possible the transformations between tidal, orthometric, and ellipsoidal vertical datums. The creation of a DEM from lidar data can be performed using different interpolation routines—each with its own advantages and disadvantages—but the NGS methodology serves to generate a nationally consistent datum-based shoreline.
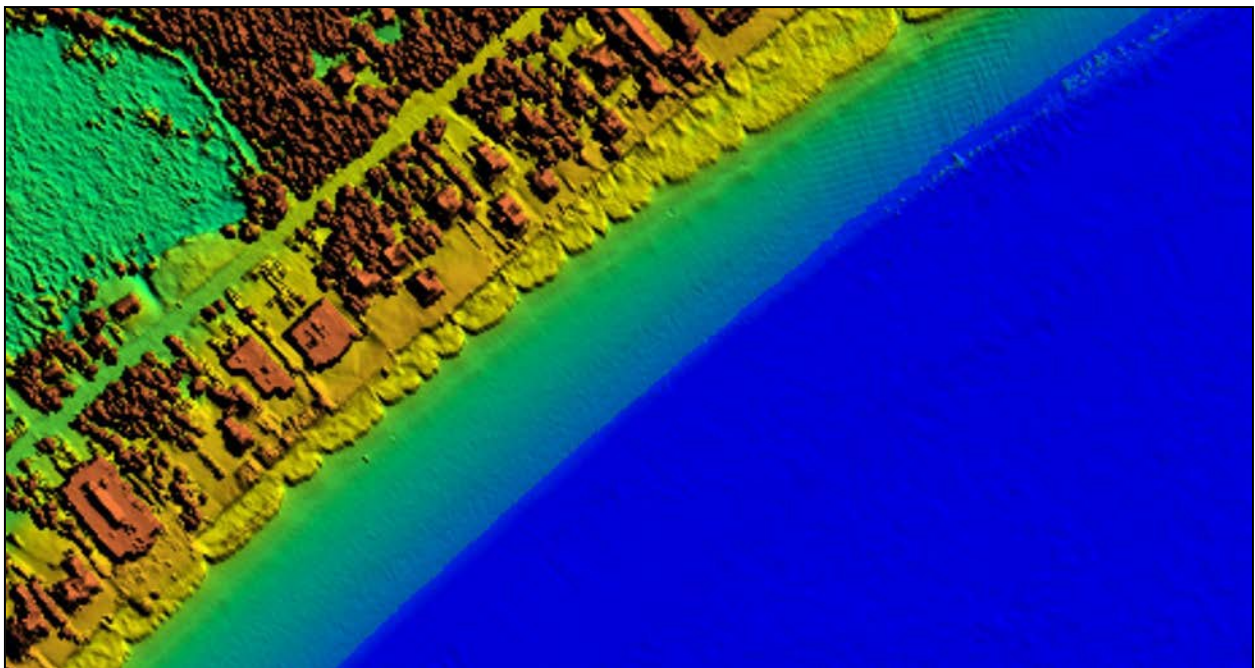

Figure 6-4. Topo-bathy DEM with MSL approximated at the transition from cyan to dark blue

Shoreline vectors are extracted from the DEM using a contour interpolation method. Figure 6-5 presents a shoreline representing MHW following the NGS workflow.

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Figure 6-5. Lidar-derived mean high water shoreline (blue line) on top of aerial photo taken around the predicted time of mean high water

As with DEM interpolation methods, there are different techniques for extracting contours. The NGS method uses linear interpolation to produce consistent and accurate shorelines. The same contouring process that was used to extract the MHW contour was also used to extract the MLLW contour (Figure 6-6). In both cases, the shorelines are displayed on top of aerial imagery that was collected around the predicted time of MHW and MLLW, respectively.

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Figure 6-6. Lidar-derived mean lower low water shoreline (blue line) on top of aerial photo taken around the predicted time of mean lower low water

In summary, this discussion on shoreline mapping focused on the NGS workflow for lidar-based shoreline mapping. As such, topo-bathy lidar points were gathered from NOAA's Digital Coast and were transformed to tidal datums using the VDatum software. DEMs were then created for each tidal datum with a 1.5 meter grid resolution. Shoreline contours were created from the DEMs and presented in the graphics.

Inundation Mapping

Inundation, whether from sea-level rise or storm surge, is a common coastal application using elevation data. Lidar data provide the accuracy to both model and delineate the potential extent of flooding from different forms of inundation due to the high accuracy of the data and the ability to resolve small features that influence flow paths. In sea-level rise scenarios, the lidar data can be used to model topographic change—or morphologic change—that would be generated from a nearly uniform rise in water level and also to identify areas that are potentially susceptible to flooding. Coastal flooding from storms represents a rise in water level that is not uniform. Lidar data can be input in surface water models as well as map flooding extent.

Storm surge is typically modeled using either the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model or the Advanced Circulation (ADCIRC) model. There are advantages and disadvantages to both models, and lidar data can be, and have been, incorporated into both models. The DEM grid that the ADCIRC model uses generally has a higher resolution than the SLOSH model, but ADCIRC cannot yet be run operationally for oncoming storms. Of course, neither SLOSH nor ADCIRC run at or near the resolution of even the coarsest lidar data. The

output of the SLOSH model is an "envelope" of water that includes water depth (Figure 6-6). When these outputs are combined with a lidar-derived topographic surface (Figure 6-7), flood areas, extents, and depths are more precisely defined than those generated using the "best available" regional data (Figure 6-8) that, in this case, has a lower spatial resolution and also poorer accuracy.
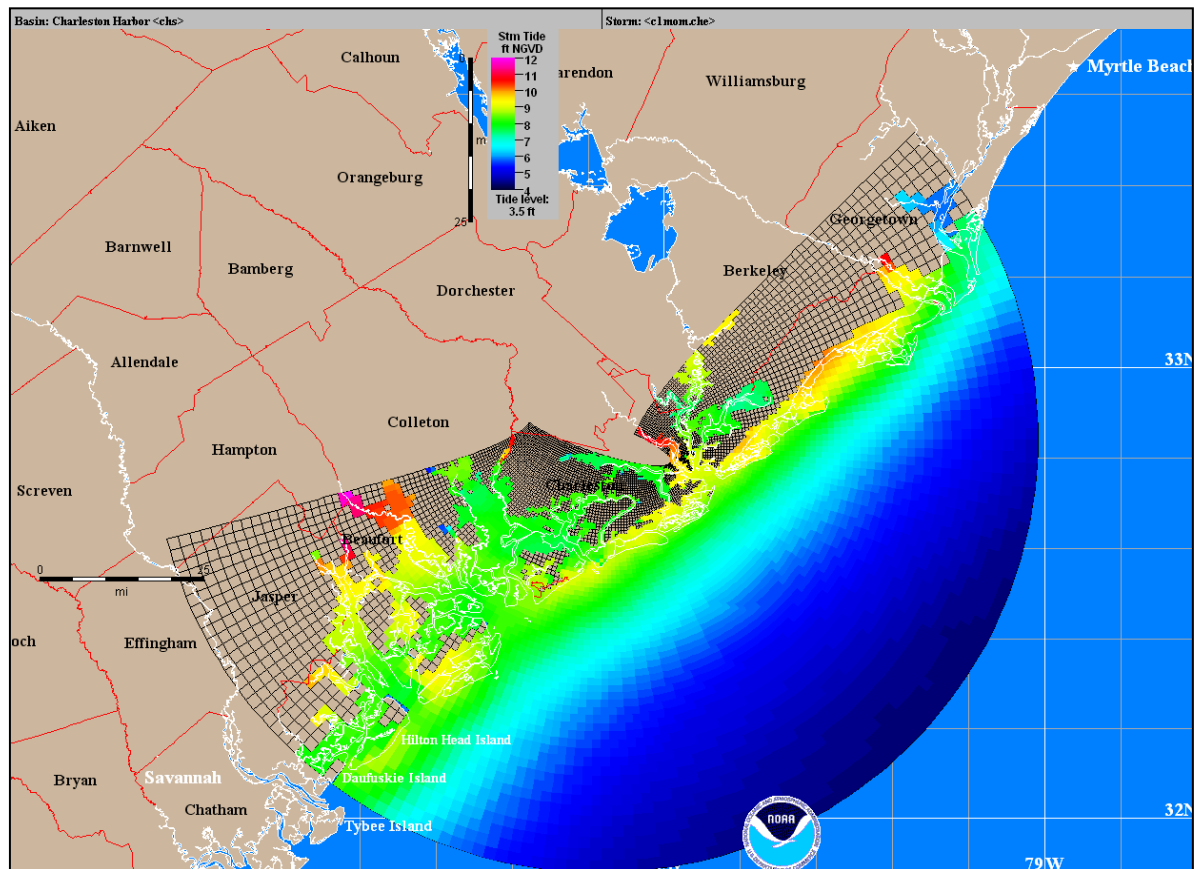

Figure 6-1. SLOSH maximum of maximums (MOM) output example for a category 1 hurricane affecting the central South Carolina coast
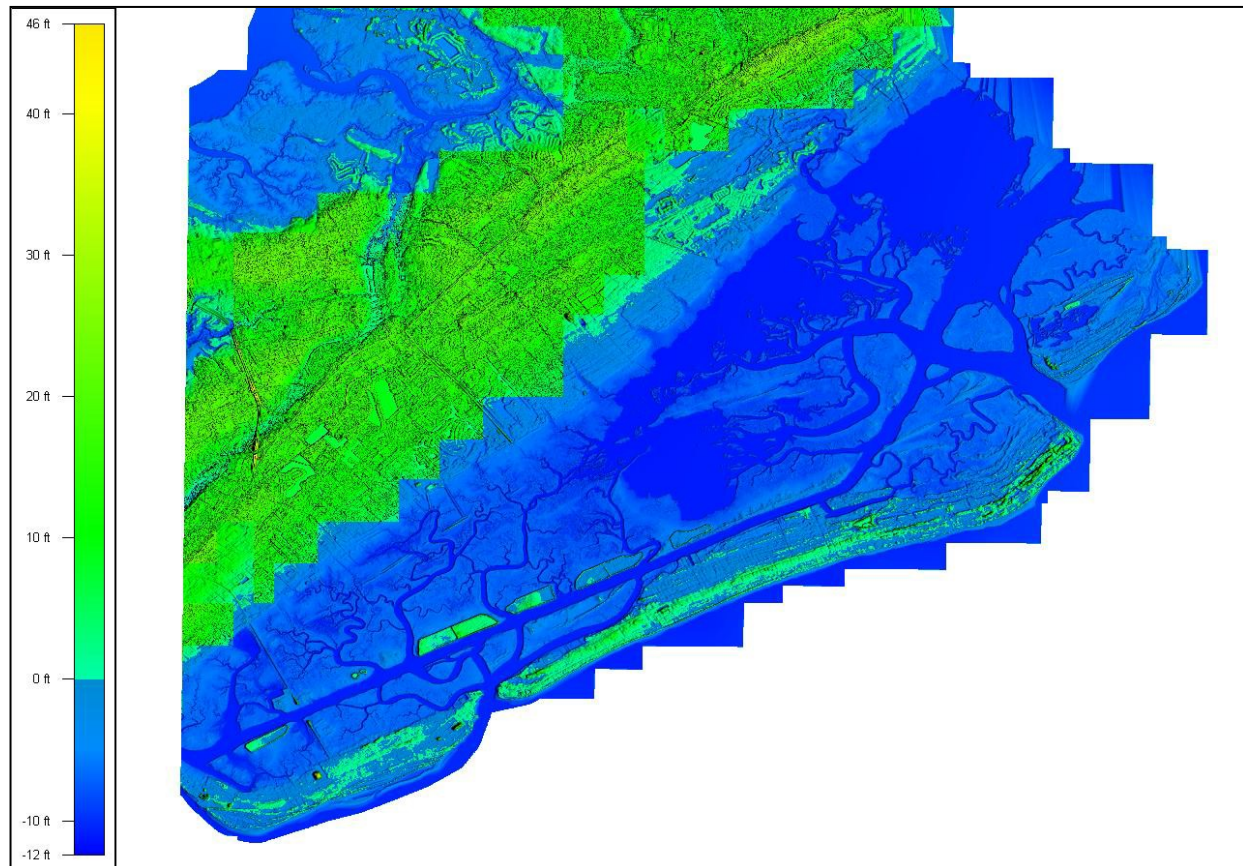
Figure 6-2. SLOSH inundation for category 1 hurricane mapped on top of lidar data in the Charleston, South Carolina Area. Blue areas are inundated (i.e., underwater); the "blocky" pattern in the center of the image reflects the coarse resolution of the SLOSH Grid.
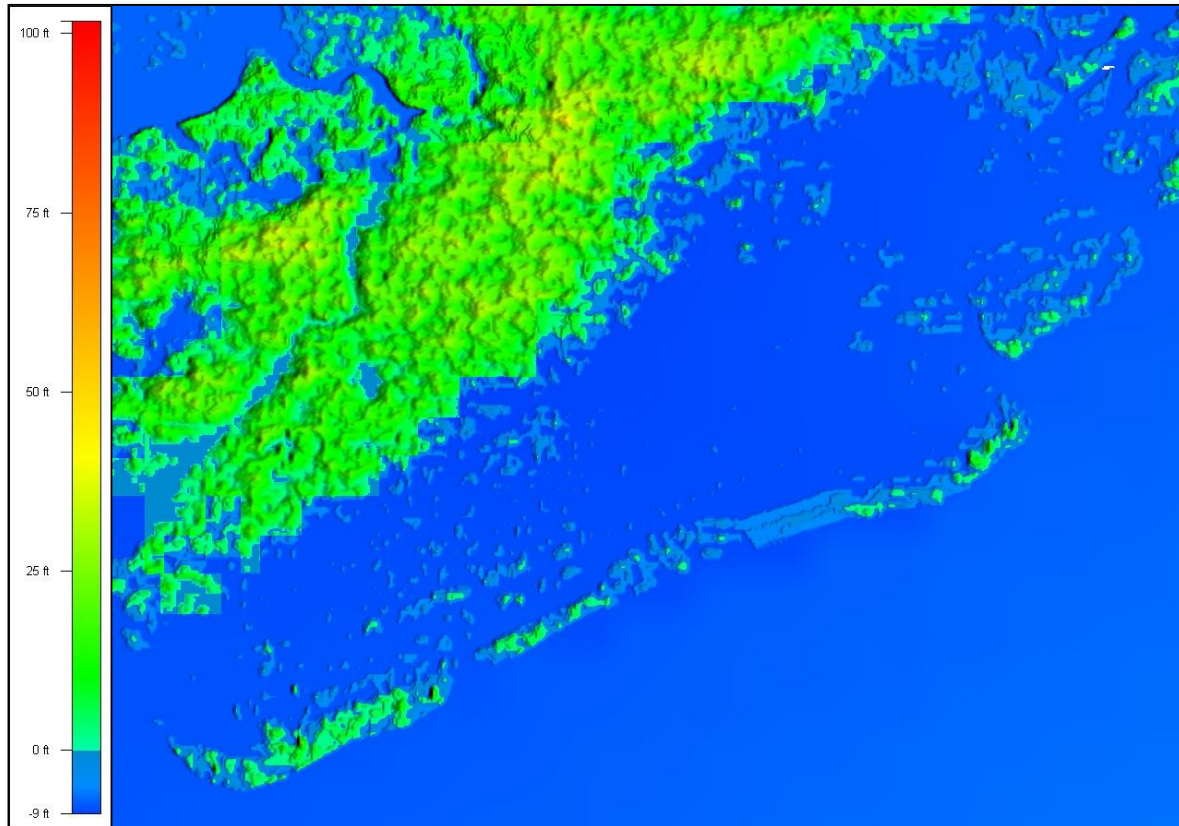
Figure 6-3. The same SLOSH inundation data and the same location as above. However, a lower accuracy National Elevation Dataset DEM is used instead of lidar; blue areas are inundated (i.e., underwater).

Wetland Habitat Delineation

Elevation is an extremely important variable in defining coastal wetland habitats (Figure 6-9), and in the face of changing sea levels, evolution in marsh micro-habitats (i.e., low marsh vs. high marsh) will depend on the sea-level change rates and ability of the marsh to accrete vertically (i.e., increase elevation through deposition of sediment and detritus). If the system lacks sediment or biogenic (e.g., plant material, shells) deposition, then the marsh habitats will migrate to higher elevations, if possible, as sea-level rises. In a system where sediment or biogenic deposition can match rises in sea-level, the marshes and their micro-habitats will continue to maintain an equilibrium. In either case, new marsh will be created, if environmental variables permit, where uplands once existed.
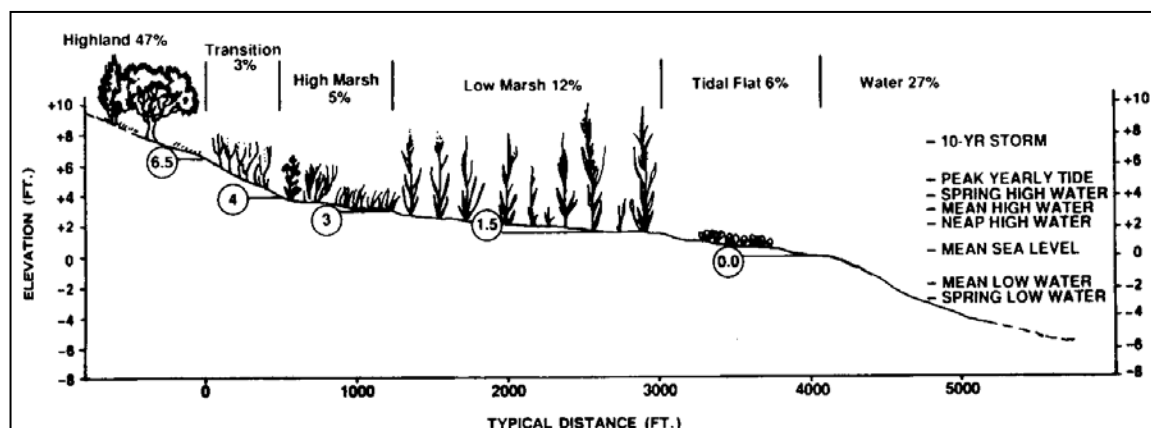
Figure 6-4. Wetland habitats along a theoretical elevation profile (Kana and others, 1988)

For example, in a report on wetland habitats in the greater Charleston, South Carolina, area, Kana and others (1988) defined the marsh habitats, species, and their relative elevation zones (Figure 6-10) and found that there were fairly narrow elevation zones for many of the species. Use of these field-measured distributions and lidar ground elevations may help further define the spatial zones (elevation based) for various species or greater marsh habitats; and, significantly, what the extent of zones would be under varying marsh accretion or sea-level rise scenarios.
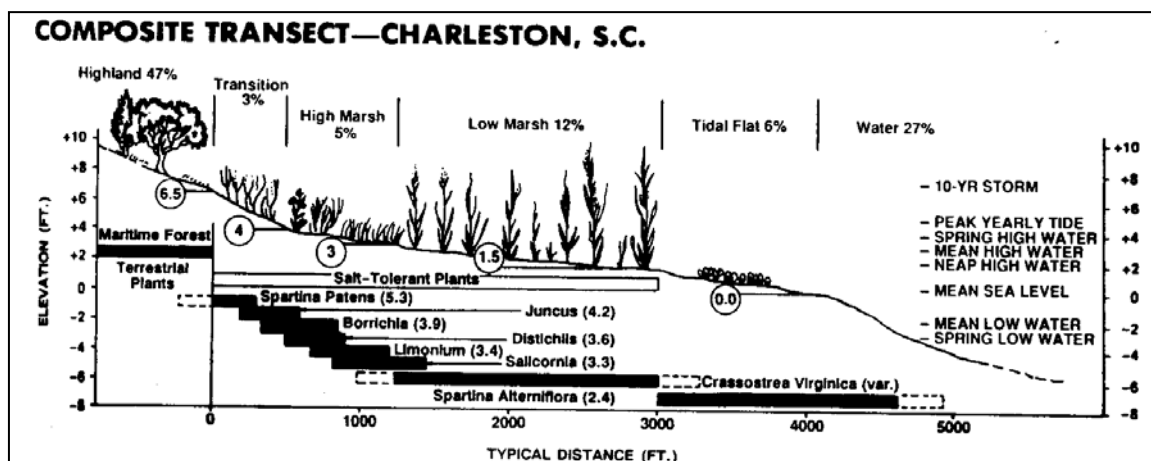

Figure 6-5. Wetland habitats and species range in Charleston, South Carolina (Kana and others, 1988)

Wetlands pose a particular challenge when working with lidar data because the upright vegetation is dense and near to the ground, and the marsh surface is partially composed of it. The following example, using lidar data from Charleston County, South Carolina, examines the use of cell size to determine the bare-earth surface in a marsh area. Even if the data are classified, the traditional routines used typically do not completely remove marsh vegetation from the data (Figure 6-11).

The lidar data were downloaded from Digital Coast using the minimum value grid method (i.e., lowest point within each grid cell) for several different grid cell sizes to approach the issue of effectively removing marsh vegetation (see Schmid and others, 2011). The cell sizes were progressively increased (Figure 6-12) to maximize the potential for capturing a point that struck the substrate (i.e., mud) rather than the flora. As shown previously, the trade-off is a decreased level of detail and imparting a potential low bias when increasing the cell size with the minimum value selection method.
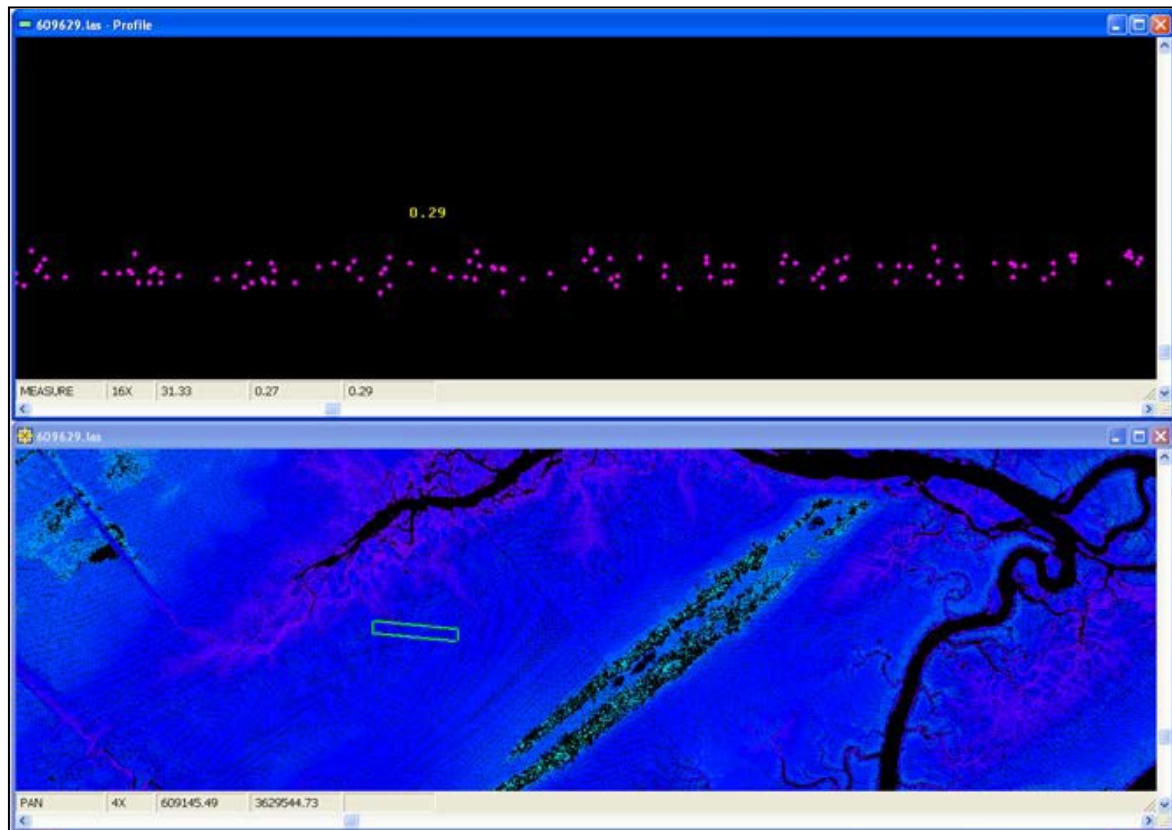

Figure 6-6. Example of lidar elevation points (ground class) in a South Carolina marsh. There is a range of about 30 centimeters (1 foot) that appears to represent the vegetation heights.
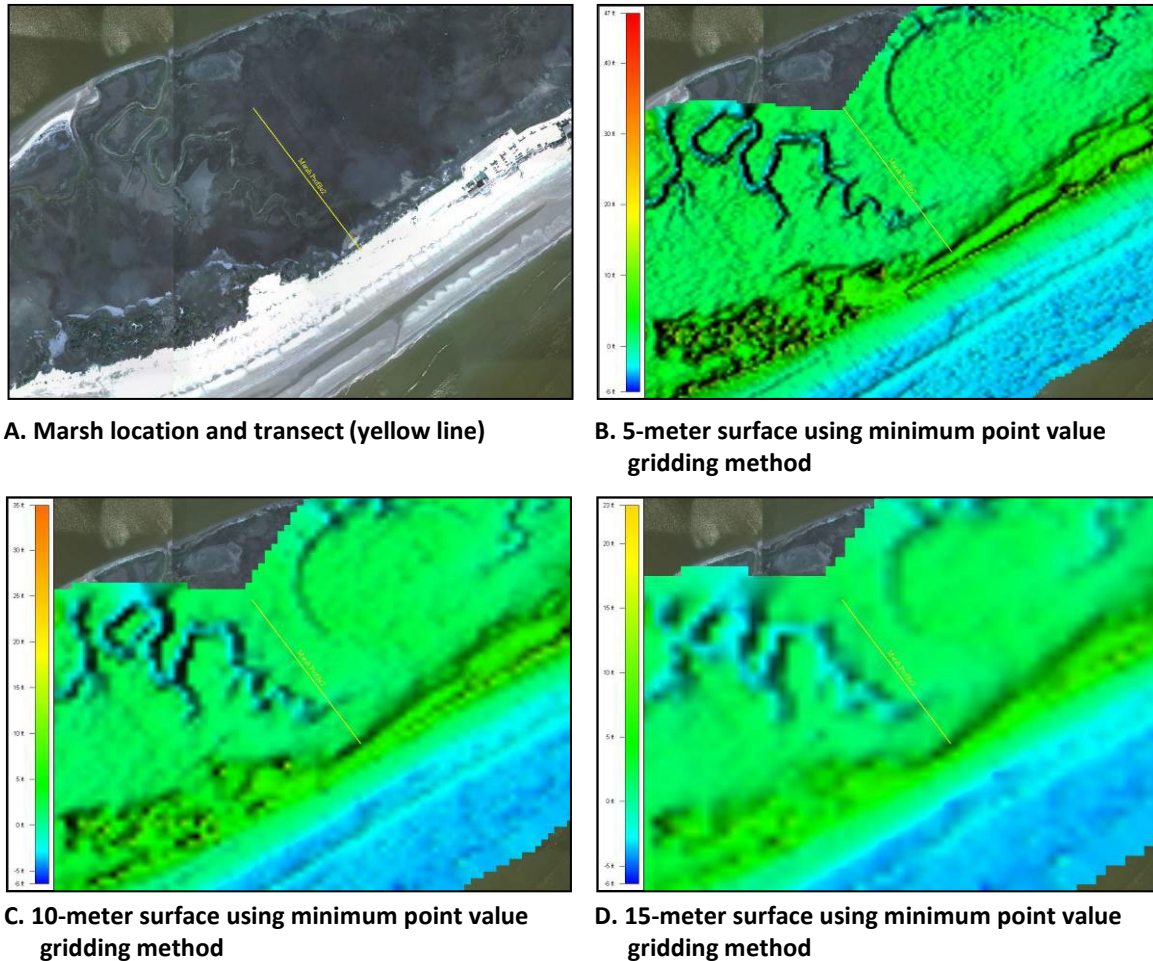
A. Marsh location and transect (yellow line)

B. 5-meter surface using minimum point value gridding method

C. 10-meter surface using minimum point value gridding method

D. 15-meter surface using minimum point value gridding method

Figure 6-7. Marsh elevations with hillshades created from different size grid cells (bins)

The lidar surface data from different cell sizes (Figure 6-12) highlights the gradual loss of resolution. The marsh profiles (Figure 6-13) from the transect in Figure 6-12A demonstrate how the increasingly large cell sizes effectively remove higher points, which are likely related to points falling on the upright marsh vegetation. The total difference between the data sets is generally only about six to eight inches—but in a marsh that difference can be large in terms of habitat zones (i.e., low vs. high marsh species). For example, when using the elevation taken from previous work (Kana and others) to map low and high marsh vegetation zones (Figure 6-14), the differences from the 3 resolutions are quite dramatic.
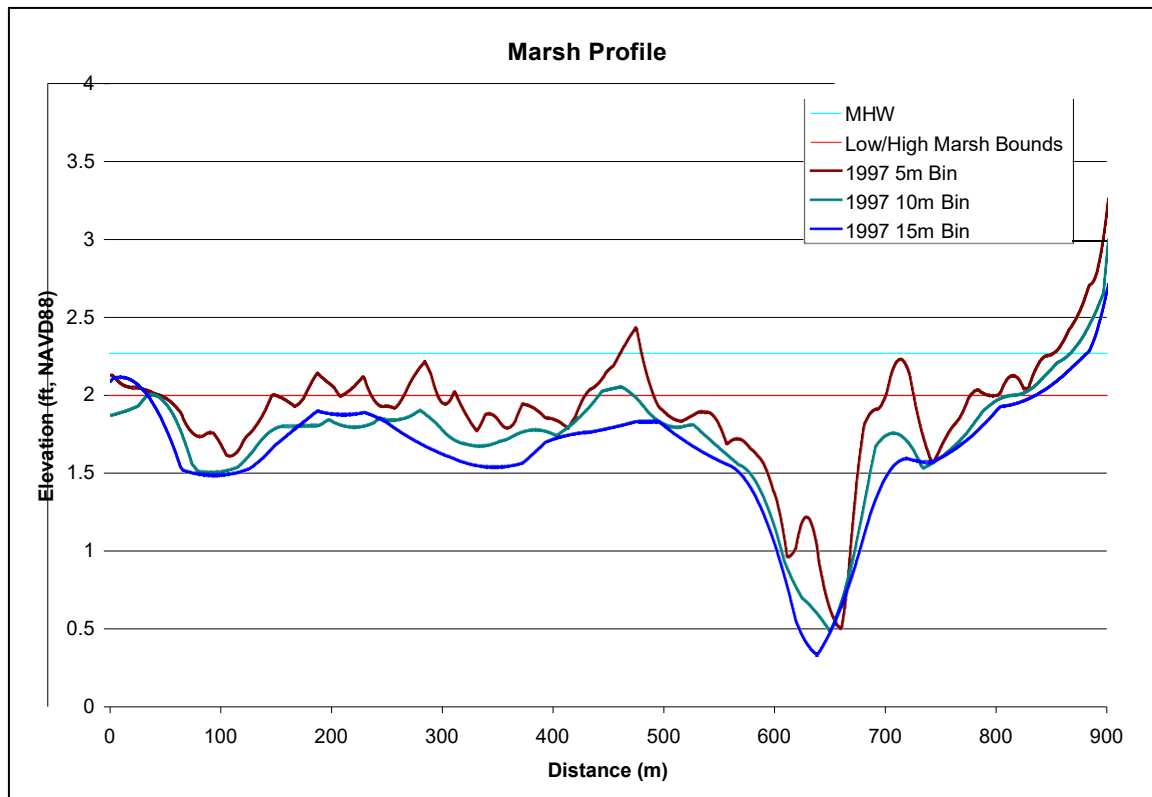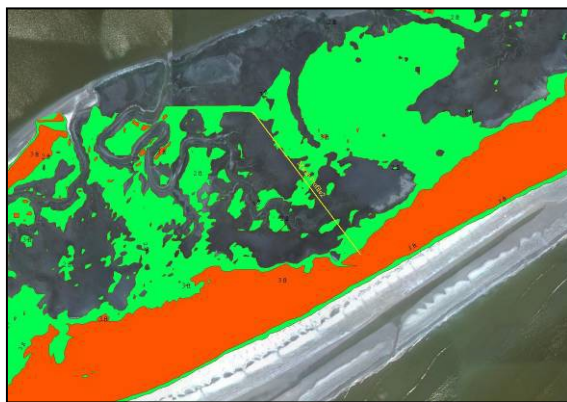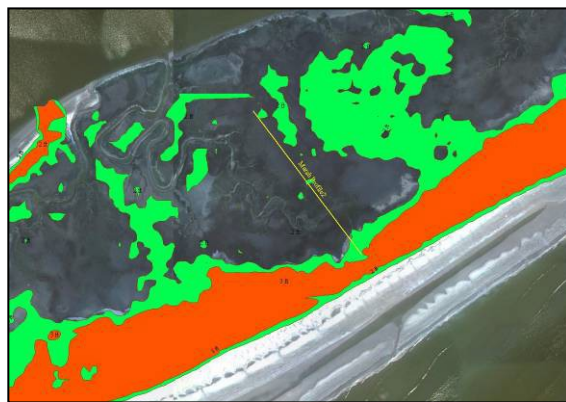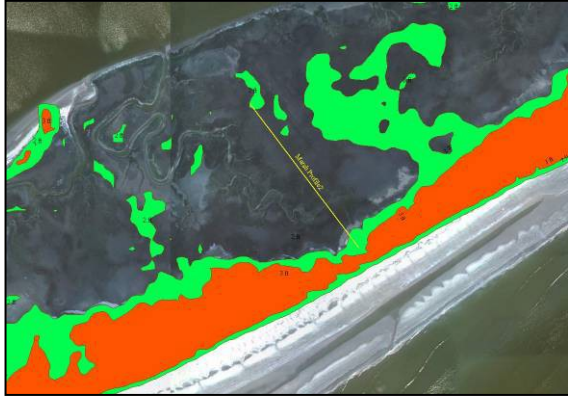
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Figure 6-8. Marsh profile along yellow transect

A. High marsh (green) from 5-meter grid

B. High marsh (green) from 10-meter grid

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C. High marsh (green) from 15-meter grid

Figure 6-9. High marsh zone (green), transitional, low marsh zone (clear), and upland (orange) zones

Further work can be done to begin looking at marsh elevation or habitat zones from different dates, using the same gridding scheme. It should be noted, however, that when comparing different data sets, there is an inherent error in the data of approximately 0.5 to 1 foot. That being said, the relative error (i.e., the error between points in the same area, not the error with respect to a set datum) should be significantly less.

A major issue in mapping the marsh surface is removing points that fall on vegetation while still honoring the slight variations in the surface. The example above (Figure 6-14) was taken from a data set that has a moderate point spacing of about 1.5 meters. A more densely sampled data set would increase the number of points striking the marsh surface over a certain area, and smaller bins could be used. While lidar is among the highest-resolution, highest-accuracy elevation data commercially available, use of the data must respect the inherent limitations of the data set. Many limitations can be overcome through additional processing, although some errors may only be minimized.

Summary

Highly accurate, high-resolution lidar data have particular utility in coastal settings where terrain is generally flat and subtle elevation changes often have significant importance. These examples represent only a small subset of applications of lidar in coastal environments. Other potential applications of lidar include forestry, geology, watershed and water quality studies, transportation, safety, cadastral mapping, and archaeology. As lidar is increasingly available for coastal areas, applications that relied on coarse data are being improved with the use of lidar data. One example of this is the ongoing work with the Federal Emergency Management Agency's Risk MAP program, where more accurate data are used to generate new flood maps.

Table of Abbreviations

ADCIRC	Advanced Circulation
ASPRS	American Society for Photogrammetry and Remote Sensing
CI	contour intervals
CVA	consolidated vertical accuracy
DEM	digital elevation model
DSM	digital surface model
DTM	digital terrain model
FEMA	Federal Emergency Management Agency
FGDC	Federal Geographic Data Committee
FVA	fundamental vertical accuracy
GCP	ground control points
GIS	geographic information system
GPS	Global Positioning System
IDW	inverse distance weighted
IMU	inertial measuring units
INS	inertial navigation systems
LABINS	Land Boundary Information System
LDART	Lidar Data Retrieval Tool
MHW	mean high water
MLLW	mean lower low water
MOM	maximum of maximums
NDEP	National Digital Elevation Program
NED	national elevation dataset
NEEA	National Enhanced Elevation Assessment
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSSDA	National Standard for Spatial Data Accuracy
RMSE	root mean square error
SLOSH	Sea, Lake, and Overland Surges from Hurricanes
SOW	statement of work
SVA	supplemental vertical accuracy
TIN	triangulated irregular network
CLICK	Center for Lidar Information Coordination and Knowledge
LADAR	laser detection and ranging
LIDAR	light detection and ranging
NMAS	National Map Accuracy Standard
USGS	U.S. Geological Survey

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