Fundamentals of Photogrammetric and LIDAR Mapping – Part 2

Florida Board of Professional Engineers

Approved Course No. 0010329

4 PDH Hours

A test is provided to assess your comprehension of the course material – 24 questions have been chosen from each of the above sections. You will need to answer at least 17 out of 24 questions correctly (>70%) in order to pass the overall course. You can review the course material and re-take the test if needed.

You are required to review each section of the course in its entirety. Because this course information is part of your Professional Licensure requirements it is important that your knowledge of the course contents and your ability to pass the test is based on your individual efforts.

Course Description:

This course material is based entirely on a design guide issued by the US Army Corps of Engineers (USACE). The course is Part 2 of 2 and covers Chapters 6 and 7 of the USACE Photogrammetric and LiDAR Mapping ENGINEERING AND DESIGN guide. Part 1 covers Chapters 4.

In Part 1 (Chapter 4) the course will review the fundamentals of Photogrammetry. Photogrammetry can be defined as the science and art of determining qualitative and quantitative characteristics of objects from the images recorded on photographs, whether hardcopy film or digital imagery. Fundamentals of the technology, its uses and applications will be discussed in the course.

In Part 2 (Chapters 6 and 7) the course will review the fundamentals of Airborne Topographic LiDAR (land based) and Airborne Bathymetric LiDAR (underwater). LiDAR is a a remote sensing technique used to measure the distance to an object by determining the time of flight for an emitted laser beam. Fundamentals of the technology, its uses and applications will be discussed in the course.

How to reach Us …

If you have any questions regarding this course or any of the content contained herein you are encouraged to contact us at Easy-PDH.com. Our normal business hours are Monday through Friday, 10:00 AM to 4:00 PM; any inquiries will be answered within 2 days or less. Contact us by:

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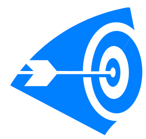
Fundamentals of Photogrammetric and LIDAR Mapping – Part 2

How the Course Works…

What do you want To do?	LOOK For This!
 **Search for Test Questions and the relevant review section**	 **Q1** **Search the PDF for: Q1 for Question 1, Q2 for Question 2, Q3 for Question 3, Etc…** **(Look for the icon on the left to keep you ON Target!)**

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24 QUESTIONS

Q1: Airborne Light Detection and Ranging (LiDAR) is also sometimes referred to as:

(A) Airborne Light Scanning
(B) Airborne Level Scanning
(C) Airborne Laser Scanning
(D) Airborne Laser Imagery

Q2: A laser system characterized as continuous wave (CW) transmits a continuous signal and ranging is determined by:

(A) modulating the intensity of the laser light
(B) modulating the wavelength of the laser light
(C) modulating the duration of the laser light
(D) modulating the aperature of the laser light

Q3: Pulse energy (total energy of the laser pulse) is measured in what units:

(A) BTU
(B) kW
(C) micro Joules
(D) milliamps

Q4: What is the name given to the measurement of the number of pulses emitted by the laser instrument in 1 second:

(A) Pulse Frequency
(B) Pulse Repetition Frequency
(C) Pulse Wave Frequency
(D) Pulse Number

Q5: A less used scanning mechanism where the laser pulsed energy is transmitted into one of the fibers arranged in a circle producing a mutating scan pattern is called:

(A) Push Broom
(B) Mutating Scan
(C) Circular Fiber
(D) Palmer Scan

Q6: Reflectance is an important consideration in LiDAR performance. Reflectance describes:

(A) the percentage of laser energy that is absorbed by an object
(B) the percentage of laser energy that is reflected off of an object
(C) the percentage of laser energy that is refracted off of an object
(D) the percentage of laser energy that is reflected off of cloud cover

Q7: Basic questions to answer when planning a LiDAR project include:

(A) Why is this dataset needed
(B) What are the specific deliverables needed
(C) When are the deliverables needed
(D) All of the Above

Q8: For a LiDAR project, Flight planning is always the responsibility of whom:

(A) the acquisition contractor
(B) the end data user
(C) the FAA
(D) A and B

Q9: For LiDAR projects where the sensors are expected to operate at above 20,000 feet above sea level, what type of aircraft provides the best performance:

(A) single engine piston
(B) twin engine piston
(C) turboprop
(D) NA there is no difference in performance

Q10: These are the well-established points that GPS ground base stations will be placed on to facilitate accurate positioning of the aircraft during a LiDAR project. One of these is called CORS which stands for:

(A) Continuously Operating Reference Source
(B) Continuously Operating Radiant Station
(C) Continuously Operating Reference Station
(D) Continuously On-call Reference Station

Q11: During a LiDAR project quality control checkpoints are typically collected by whom:

(A) the acquisition contractor
(B) the end data user
(C) the FAA
(D) an independent survey team

Q12: Classification is the process whereby the acquired LiDAR points are filtered. Which Class is considered Bare-earth Ground:

(A) Class 1
(B) Class 2
(C) Class 7
(D) Class 9

Q13: **Breaklines are commonly collected for the following features:**

(A) Streams and Rivers
(B) Ponds and Lakes
(C) Hydro Flattened DEM Production
(D) All of the Above

Q14: **Airborne LiDAR Bathymetry (ALB) is a surveying and mapping technology that uses WHAT type of laser pulse in order to measure underwater elevations:**

(A) blue
(B) green
(C) blue-green
(D) red

Q15: **The primary user of ALB technology in the US Army Corp of Engineers is what program:**

(A) National Coastal Monitoring Program
(B) National Coastal Mapping Program
(C) National Coastal Progression Program
(D) National Coastal Movement Program

Q16: **The ALB technique relies on propagation of laser pulses through the water and to:**

(A) be absorbed in coral structures
(B) be reflected off of the water surface
(C) be reflected off of the sea bed
(D) be reflected off of the first 5 feet of surface water level

Q17: **What is one of the major cost drivers for any airborne survey:**

(A) size of the data set
(B) the desired resolution
(C) number of reference stations available
(D) flight time to cover the survey area

Q18: **The amount of suspended sediment and organics in the water column is called:**

(A) Total Organic Content
(B) Suspended Solids
(C) Turbidity
(D) Dissolved Solids

Q19: **Recommended acquisition requirements for ALB surveys include reference datums such as:**

(A) Horizontal Control Datum
(B) Horizontal Control Datum
(C) Resolution Datum
(D) A and B

Q20: The effective location of the submerged surface mapped by a laser beam is much more complex to determine because of:

(A) water surface waves
(B) effect of water clarity
(C) shape and reflectivity of the submerged surface
(D) All of the Above

Q21: The major difference between traditional topographic LiDAR and topographic data collected by ALB sensors is:

(A) laser footprint size
(B) laser wavelength
(C) flying height
(D) A and C

Q22: ALB sensors are flown lower than topographic LiDARs usually between what altitudes:

(A) 300 and 600 meters
(B) 600 and 1000 meters
(C) 1000 and 1500 meters
(D) 1500 and 2000 meters

Q23: Orthomosaics at WHAT resolution are the recommended deliverable for aerial photography:

(A) 6 inches
(B) 1 foot
(C) 2 feet
(D) 3 feet

Q24: When collecting topographic data, Elevations shall be verified through comparison with ground truth data with an accuracy specification of WHAT:

(A) 1 meter Vertical
(B) 1 meter Horizontal
(C) 10 centimeters Vertical
(D) 10 centimeters Horizontal

END OF TEST QUESTIONS

US Army Corps
of Engineers

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30 April 2015

ENGINEERING AND DESIGN

Photogrammetric and LiDAR Mapping

ENGINEER MANUAL

CHAPTER 6

Airborne Topographic LiDAR

Q1

6-1. Technology Overview. Airborne Light Detection and Ranging (LiDAR) System, sometimes referred to as Airborne Laser Scanning (ALS), is a remote sensing technique used to measure the distance to an object by determining the time of flight for an emitted laser beam. A scanning mechanism (such as an oscillating mirror) is normally employed to steer a series of laser pulses (typically over 100 KHz) over a wide area from an airborne platform. All airborne LiDAR systems use enabling technologies such as Global Positioning System (GPS) and Inertial Measurement Unit (IMU) to determine the location and orientation of the remote sensor located on the airborne platform (see Figure 6-1). The resulting data are typically used to measure topography of the land surface, including bare earth topography that excludes buildings and vegetation.

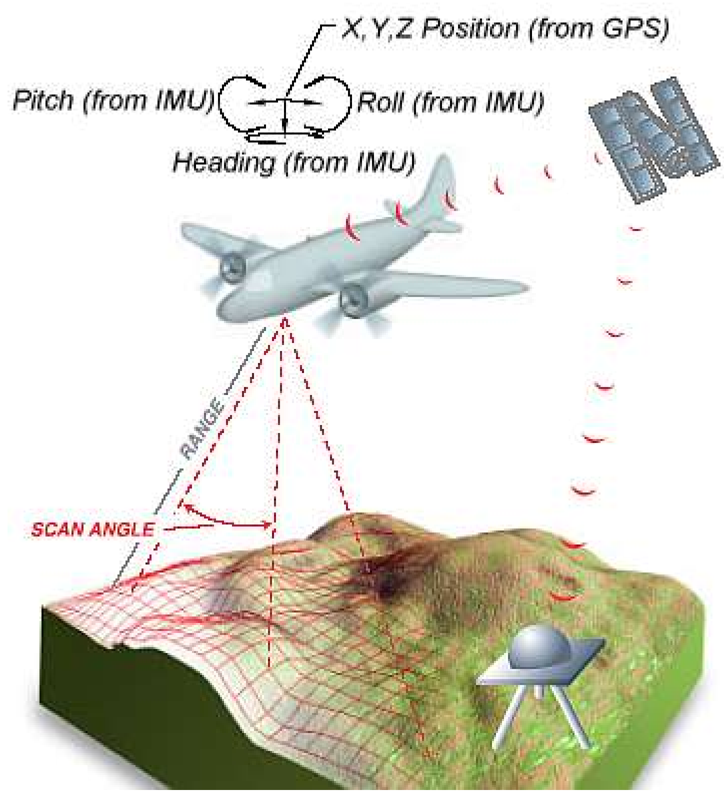

Figure 6-1. Airborne LiDAR technology is used to measure topography using a laser beam directed towards the ground with GPS and IMU systems providing the location and orientation of the airborne platform.

Q2

a. Operating Principles. Although most commercially-available Airborne LiDAR Systems use a pulsed laser source, there are other operating modes of laser-based remote sensing systems. For example, a laser system can be characterized as a continuous wave (CW) laser system that transmits a continuous signal, and ranging is determined by modulating the intensity of the laser light. In such a system, a sinusoidal signal is received with a time delay. The travel time is directly proportional to the phase difference between the received and transmitted signal. Pulsed laser systems, on the other hand, transmit a series of laser pulses and measure the round-trip time of each laser pulse that scattered back to the optical receiver. The distance (or range) to the target is determined by the one-way time of flight of the laser pulse multiplied by the speed of light.

(1) Laser. The laser ranging unit in airborne laser scanning will include the actual laser; the transmitting and receiving optics; and the receiver with its detector, time counter and digitizing unit.

(2) Laser Wavelength. For topographic mapping using airborne laser scanning, where high energy pulses are required to perform distance measurements over long ranges, only certain types of solid-state, semiconductor, and fiber lasers have the specific characteristics – ability to produce high intensity collimated beams – that are necessary to carry out these operations. Nearly all airborne topographic LiDAR systems that use solid-state crystalline material such a neodymium-doped yttrium aluminum garnet (Nd:YAG) lasers operate in the near-infrared wavelength range (typically 1064 nm). Fiber lasers (sometimes referred to as glass lasers) operating at or near 1550 nm have also been routinely used, though these systems operate at lower power levels and cannot reach the same operating altitudes as the 1064 nm laser sensors. Lasers have also been developed to operate at 905 nm, but are not very popular for airborne LiDAR applications due to their low-intensity returns over saturated sediments. Another class of lasers operates at the frequency-doubled blue-green wavelength of 532 nm. These sensors are typically used in bathymetric and topobathymetric applications because the green-wavelength laser is able to penetrate through the water column under certain conditions; see Chapter 7 for more details.

Q3

(3) Pulse Energy, Pulse Width, and Beam Divergence. The pulse energy, measured in micro Joules (µJ), is simply the total energy of the laser pulse. Pulse duration, measured in nanoseconds (ns), is typically defined as the time during which the laser output pulse power remains continuously above half its maximum value. Beam divergence, measured in milliradians (mrad), refers to the increase in beam diameter that occurs as the distance between the laser instrument and a plane that intersects the beam axis increases. The pulse energy of topographic LiDAR systems are typically low (10-100 µJ) to allow for a tightly focused beam with low beam divergence that is also eye safe. Bathymetric LiDAR systems have pulse energies up to 7 mJ, which are typically much higher than the near-infrared lasers used in topographic applications. The higher power is needed for the laser pulse to penetrate through the water column to map the bottom. The bathymetric sensors with very high laser pulse power also have a large footprint so that the energy is spread across a larger area for eye-safety reasons. The pulse width determines the range resolution of the pulse in multiple return systems (explained below), or the minimum distance between consecutive returns from a pulse. Traditionally, pulse widths for topographic systems have been in range of about 10 ns. This means that there is a “blind spot” of about 1 meter along the laser path behind each received LiDAR return. Newer laser technology has enabled the use of much shorter pulse widths (1-2 ns) for topographic and topobathymetric applications. For topobathymetric applications, a short pulse width laser enables the separation of a return from the water surface and bottom in very shallow water depths. This limits the effective measurement depth to >0.5m for threshold detect topobathy LiDAR systems.

Q4

(4) <u>Pulse Repetition Frequency (PRF)</u>. The PRF, measured in kHz, is the number of pulses emitted by the laser instrument in 1 second. Older instruments emitted a few thousand pulses per second. Modern systems can support frequencies of 400 kHz and newer technologies are now enabling 2 lasers channels to be used in conjunction with the same scanning mirror, thereby producing effective PRF of 800 kHz. Many systems allow different settings for the PRF. This is usually done to allow the systems to fly at different flight altitudes. The PRF is directly related to the point density on the target. For example, a system operating at 167 kHz from the same flying altitude will have higher number of returns than when operating at 100 kHz. Equivalently, a high PRF system can generate desired return densities by operating on an aircraft that flies higher and faster than an aircraft carrying a lower PRF system, thereby reducing flying time and acquisition costs when weather conditions allow for higher flying altitudes.

b. <u>Scanner</u>. The primary goal of the scanning technique is to create a wide swath with consistent along- and across-track point spacing, and reliable and accurate elevations for the entire swath. Several scanning techniques have been used in airborne LiDAR systems. In theory there are no special reasons why one scanning technique is preferable to another, although scan patterns that facilitate constant incident angle on the terrain can reduce data voids related to dynamic range of the receiving optics. The most common scanning techniques are the Oscillating Mirror and Rotating Mirror.

(1) <u>Oscillating Mirrors</u>. In systems using an oscillating mirror, the mirror rotates back and forth between limited extents, producing a zigzag (i.e. sinusoidal pattern) line on the surface of the target area (Figure 6-2). The mirror is always pointing downwards towards the ground so data collection can be continuous and theoretically all pulses of the laser can be used. The field of view and scan rate can be set by the operator prior to acquisition. Changing the field of view provides additional flexibility as it allows laser pulses to be collected over a shorter span (denser data) or a wider span (sparser data). Although the oscillating mirror is the most widely used scanning mechanism for airborne LiDAR systems, there are inherent disadvantages of using the oscillating mirror principle. The changing velocity and acceleration of the mirror as it oscillates from one end to the other causes unequal spacing of the laser pulses on the target. The point density increases along the edges of the scan where the mirror slows down, and decreases along the center in the along-scan direction. The forward motion of the aircraft causes the zig-zag pattern with varying point spacing along the edges of the scan in the cross-scan direction. Manufacturers have solved these problems by essentially ignoring the outlier

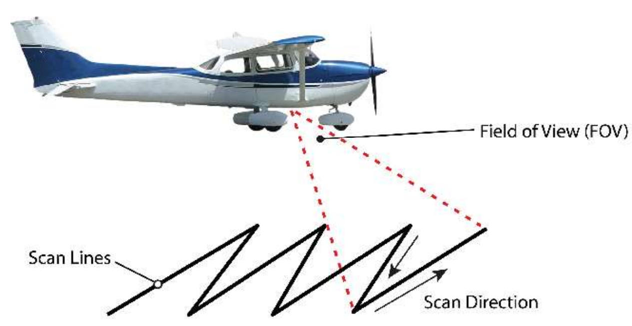

Figure 6-2. Sample scanning pattern produced by an oscillating mirror. The forward look angle of the scanner is for illustrative purposes only. Most scanners operate near nadir-looking scanners when using oscillating mirrors.

points on a scan and modeling the distortions caused by changing speed using a computer algorithm.

(2) Rotating Mirrors. The rotating mirror is another commonly used scanning mechanism for airborne LiDAR systems. In this approach, the mirror is rotated continuously at a constant velocity in one direction producing a parallel line scan (Figure 6-3). The constant velocity ensures that there are no acceleration type errors encountered in the oscillating mirror scanner. The point spacing is also more regular both along and across the scan. However, the biggest disadvantage is that observations cannot be taken during a significant time during each mirror rotation when the mirror is pointing away from the target. Typically, 30-40% of the emitted laser pulses are not aimed at the target area and are essentially lost to the scanning mechanism.

Q5

(3) Other Scanning Patterns. Other scanning mechanisms less commonly used include the push broom (fiber scanning) pattern where the laser pulsed energy is transmitted into one of the fibers arranged in a circle producing a nutating scan pattern (Figure 6-4) and the Palmer scanner that produces an elliptical scanning pattern with redundant data that can be used for calibration or to get a forward and aft view of the same target (Figure 6-5).

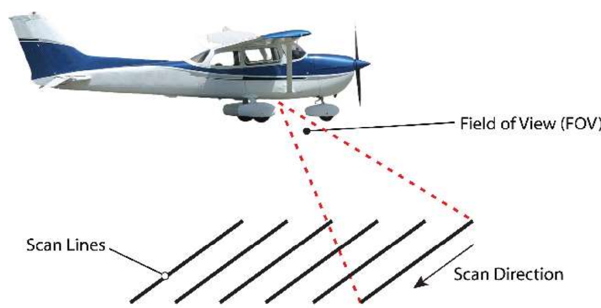

Figure 6-3. Sample scanning pattern produced by a rotating mirror

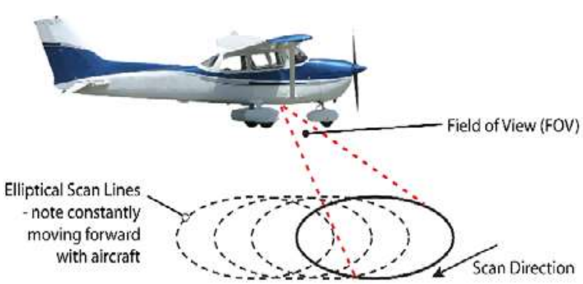

Figure 6-4. Sample scanning pattern produced by a push broom fiber scanning pattern

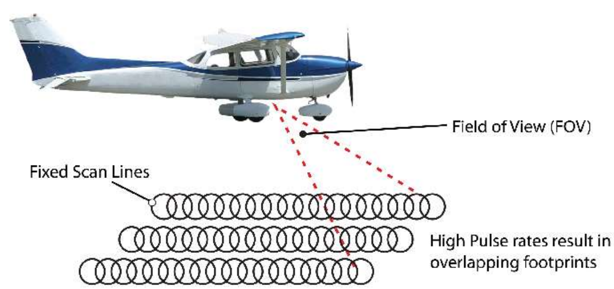

Figure 6-5. Sample scanning pattern produced by a Palmer or elliptical scanning pattern

c. Geopositioning. Calibrating LiDAR data begins with the proper installation/mounting of the LiDAR unit, GPS antenna, and IMU sensor on the aircraft, and the precise measurement of offsets in the x, y, and z directions between each of these sensors. The IMU usually serves as the point of reference and the precise distance between all units are measured with respect to the IMU. The precise location of the GPS base station, the antenna height, and the phase center information are required to process the differential GPS-IMU trajectory. The GPS-IMU trajectory is the precise aircraft trajectory that contains the 6 positioning and orientation parameters: x, y, z, pitch, roll, heading; along with a unique timestamp. The position information is derived from post-processing the aircraft GPS receiver data along with the GPS base station data using specialized differential GPS (DGPS) software. The LiDAR positions are calculated at 0.5 second steps. In a second step, an integrated position and orientation solution is calculated with the DGPS-position data and the IMU data by another software module, yielding position and orientation (roll, pitch, yaw) angles to better than one-hundredth of a degree. The IMU measurement rate is typically 200 Hz; the trajectory values are usually maintained at the same rate as the IMU, i.e. 200 records per second. Once the GPS and IMU data are processed and passes all QC checks, the data are combined with the laser range data. This processing step is performed in the LiDAR manufacturer's developed software. Calibration is done at this stage of the processing. Although the methods of performing calibration are software-dependent (and hence manufacturer-dependent), the LiDAR vendor should test the calibrated data independently. This is usually done by interrogating data from four overlapping flight lines flown in opposite and perpendicular directions along building rooftops and flat surfaces such as airport runways. Any misalignment between the IMU and the LiDAR scanner can be determined using this approach. This information can be fed back into the calibration software to improve the overall calibration of the data. Calibration testing is recommended prior to each mission and is necessary when any of the LiDAR system components are remounted on the aircraft. Several different types of airborne LiDAR systems were developed in the research and scientific field since the late 1970s through the 1980s. These systems typically involved the use of laser profilers to generate a single line profile of the ground beneath an aircraft. The development of Global Positioning System (GPS) and Inertial Measurement Unit (IMU) technologies in the 1990s for civilian applications eventually led to the use of airborne LiDAR systems for accurate topographic mapping. The development of laser scanners (explained in Section 6-1.b above) during the same decade also enabled the use of these systems for wide-area topographic mapping. Airborne LiDAR systems can be broadly classified based on the following specifications: (1) Laser wavelength (2) Pulse energy, pulse width, and beam divergence; (3) Pulse Repetition Frequency (PRF); (4) Operating Altitude; and (5) Return type.

d. Operational Considerations

Q6

(1) Reflectance. Reflectance is an important property that affects LiDAR performance. The amount of energy that arrives back at the LIDAR receiver is directly proportional to the percentage of energy that reflects off the object, or in other words the object's reflectance. The reflectance of the object is wavelength-dependent, and because LiDAR systems are monochromatic, the reflectance at that particular wavelength determines how detectable an object is given the laser power. Figure 6-6 shows the relative spectral reflectance of various common landscape materials.

(2) Operating Altitude. The operating altitude for an airborne LiDAR system is largely dependent on the required point density of data and the ability of the laser to reliably detect returned energy and determine the elevation of a target at varying reflectivities. Some LiDAR

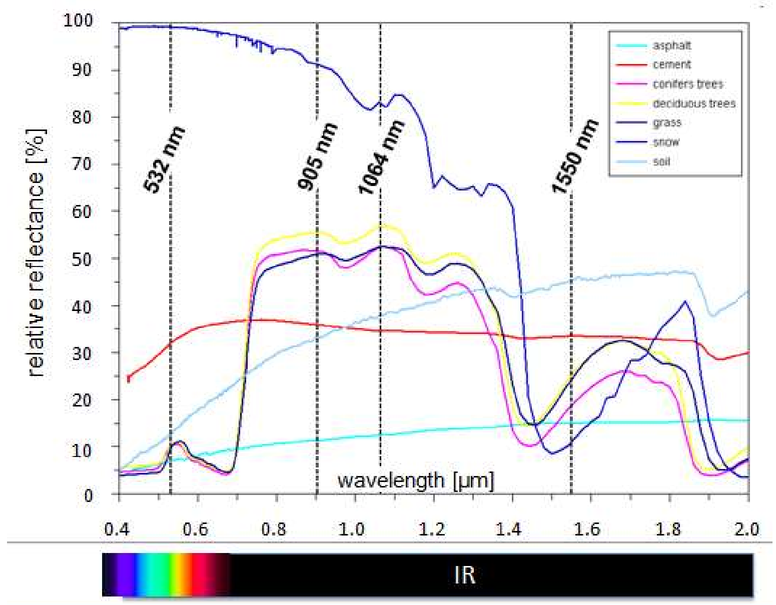

Figure 6-6. Spectral reflectance of various common landscape materials. The common wavelengths used by lidar sensors is also shown. Image courtesy Riegl, GmbH.

systems are specifically designed as low-altitude sensors with relatively low pulse energy. These systems have typically high PRFs that enable the acquisition of 20-50 points per square meter at operating altitude of 500-3000 ft. Other systems are designed to be used at much higher operating altitudes (3000-8000 ft). These systems are designed for wide-area mapping with swath widths that can extend to 1500 meters. Until early 2006, high-altitude sensors were limited by the inability to track multiple pulses in air (MPiA). For these sensors without MPiA capability, an emitted laser pulse had to bounce off the target and be received by the sensor before the next pulse could be emitted. As a result, the PRF and operating altitude had to be limited in order to have only 1 pulse in the air at any instant of time. Recent developments in firmware now allow the tracking of MPiA, also known as Multiple Time Around (MTA), and some sensors can track up to 8 pulses in the air. MPiA technology has enabled LiDAR sensors to use 2 laser sources simultaneously (dual-channel lasers), thereby producing 800 KHz PRF and the ability to operate at altitudes of over 7000 ft.

(3) Return Type. Early versions of airborne LiDAR systems were capable of recording only one pulse at low pulse repetition rates. However, more advanced LiDAR systems can record simultaneously multiple returns for each transmitted pulse, and the reflected intensity for each return. Multiple return LiDAR systems are very useful in forestry applications or even to derive bare Earth topography under vegetation. When the laser beam from a multi-return system interacts with a tree canopy, then the first return is usually assumed to arrive from the top of the tree (or where the transmitted laser beam first interacts with the tree canopy). The last return may interact with the ground underneath the tree, although the ability to map the ground is largely dependent on the density of the vegetated canopy. Intermediate returns, perhaps 2nd, 3rd, and 4th, are expected to be caused by tree branches and understory vegetation between the top of the canopy and the ground.

6-2. Project Specifications. Numerous sensor parameters affect the desired quality and specifications of the LiDAR data. The USGS LiDAR Base Specification Version 1.2, at Appendix F, provides three of the most common LiDAR Quality Level (QL) specifications relevant to USACE. QL1 LiDAR (with 1-foot contour accuracy and 8 points/m^2), and QL2 LiDAR (also with 1-foot contour accuracy but with 2 points/m^2) both ensure that the point cloud and derived data products are suitable for the inter-Agency National 3D Elevation Program (3DEP); whereas QL3 LiDAR (with 2-foot contour accuracy and 0.5 point/m^2) ensures that the bare-earth DEMs derived from LiDAR data are suitable for ingestion into the National Elevation Dataset (NED). Using the USGS Lidar Base Specification at any of these three Quality Levels will ensure that USACE is consistent with the goals of the National Digital Elevation Program (NDEP) for which USACE is a key member and participant. Also see the ASPRS Positional Accuracy Standards for Digital Geospatial Data, at Appendix D, from which the Elevation Data Vertical Accuracy Standards were extracted in Chapter 3, Table 3-6. LiDAR point density and vertical accuracy are the two main cost drivers of an airborne LiDAR survey. LiDAR data can be collected with a wide variety of point densities depending on the needs of the project. The selection of point density is a big driver of the overall cost of a LiDAR project and should be selected with consideration to the end uses for the LiDAR. A LiDAR product with 1 point per square meter (ppsm) is sufficient for many applications such as flood mapping in many areas. Higher point densities (4-8 ppsm) allow for greater utilization of the data for mapping planimetric features such as roads and structures as well as for vegetation analysis such as biomass and canopy studies. Additionally, specialized LiDAR at very high densities > 20 ppsm are often used for mapping infrastructure in greater detail such as power lines, pipelines, and for significant features such as mile posts and signs. The ground conditions should be considered when selecting a point density as well. If the area is covered with dense vegetations such as a coniferous forest a higher density and more overlap would be required to penetrate to the ground than an area where leaf-off conditions exist. Vertical accuracy requirements are defined by Table 3-21 Recommended Survey and Mapping Specifications for USACE Applications. Other specifications to consider include:

a. Geographic area to be mapped (normally based on government-provided shapefiles);

b. Returns per pulse (typically is 3 or more including, first, last, and intermediate returns);

c. Collection conditions (e.g., ground is snow free, vegetation is leaf-off);

d. Ground control and/or direct georeferencing requirements (airborne GPS and IMU positioning and orientation), if any;

e. GPS base station limitations, if any;

f. Data void guidance, if any (void areas are allowed over open water and typically wet or very new asphalt);

g. Vertical accuracy (using current ASPRS and NDEP methods where NVA is tested as $Accuracy_z$ ($RMSE_z$ x 1.9600) and VVA is tested using the 95th percentile); NVA and VVA definitions are provided in Chapter 3 of this manual;

h. Horizontal accuracy (normally compiled to meet a specified value rather than tested to meet a specified accuracy value);

i. Relative accuracy (threshold, typically stated in terms of RMSE, of vertical offset between adjacent flight lines);

j. GPS-IMU trajectory solutions should be delivered and assessed for combined vertical separation between the forward and reverse trajectory solutions;

k. Tiling schema including size of final tiles and naming convention (e.g., 1,000 meter grid with no over-edge named according to the U.S. National Grid);

l. Horizontal datum (e.g., North American Datum of 1983 (NAD83)/2011 adjustment);

m. Vertical datum (e.g., North American Vertical Datum of 1988 (NAVD88), using the most recent National Geodetic Survey (NGS)-approved GEOID model for conversions from ellipsoid heights to orthometric heights, currently GEOID12A;

n. Coordinate system (e.g., UTM or State Plane Coordinate System);

o. Vertical and horizontal units (e.g., meters, or U.S. Survey Feet) – note, never specify "feet" but instead specify U.S. Survey Feet or International Feet;

p. What classes are required (e.g. 1-unclassified, 2-ground, 7-noise, 8-model key points, 9-water, 12-overlap, etc) (See section 6-4.c. for a description of classifications);

q. Processing requirements (e.g., percentage of elevated features allowed to remain in the ground classification, guidelines for over-smoothing/inconsistent editing, thresholds for artifacts/spikes/divots/cornrows, uniformity of point distribution);

r. File format (industry standard is LAS format following ASPRS formatting guidelines and specifications);

s. Compression (e.g., are compressed files allowed, if they are to be delivered in addition to or in replacement of non-compressed files, and what format should be used for the compressed files);

t. Ff intensity imagery is required, specify the resolution or pixel size;

u. If breaklines are to be collected, specify types of breaklines, minimum size for collection, monotonicity/connectivity requirements or topology rules that must be followed, and desired final format of the breaklines (e.g. ESRI shapefile, ESRI geodatabase, DXF, DGN, etc.);

v. If DEMs (such as bare-earth DEMs or first return DSMs) are to be created, specify the pixel resolution, hydro-flattening or hydro-enforcement requirements, and final format (ESRI Grid, IMG, GeoTIFF, etc.);

w. If contours are to be created, specify the interval, coding (intermediate, index, etc), level of smoothing to be applied (e.g. engineering grade, moderately smooth, cartographic grade), and the desired final format (e.g. ESRI shapefile, ESRI geodatabase, tiled, non-tiled);

x. Metadata requirements such as those defined in the IAW geospatial manual;

y. QA/QC procedures;

z. Reports to be submitted (e.g., survey report with field work procedures, data acquisition report, calibration procedures, production report, QA/QC report); and

aa. Deliverables and due dates.

Please note, however, that USACE managers should make every effort to utilize existing ASPRS standards and specifications listed above to ensure that the data will be interoperable, usable and available to others.

Q7

6-3. <u>Project Planning</u>. There are numerous requirements to assess when planning a LiDAR project as shown in the specifications section of this chapter. However, regardless of the specific requirements project planning always starts with the basic questions: Why is this dataset needed? What are the specific deliverables that are needed? When are the deliverables needed?

a. <u>Review of Project Specifications</u>. Planning is performed after careful review of the project specifications and answering a series of questions: Should maps be compiled to NAD83 (HARN) for the horizontal datum and NAVD88 for the vertical datum? Should elevation data (orthometric heights) be produced by converting from ellipsoid heights using the GEOID12A model? Should the coordinate reference system use the relevant State Plane Coordinate System or Universal Transverse Mercator (UTM) coordinates? (Note: State Plane coordinates are more accurate for typical USACE requirements). Should the units be feet or meters? If feet, should U.S. Survey Feet or International Feet be used? What should be the nominal point density? What classifications should be included i.e., ground, water, buildings, vegetation, etc? Are planimetric features such as roads or buildings needed to be extracted from the LiDAR data? Are there limits on environmental factors such as shadows, clouds, topography, climate, snow cover, standing water, tidal and river levels? Will DEMs, DSM, Contours, or other derivative products be produced? What are the metadata requirements? How are accuracies to be reported in the metadata; will the accuracy be reported using the accuracy at the 95% confidence level for the NVA? Are waveform data needed? If yes, what is the data format?

(1) LiDAR Point Density. LiDAR data can be collected with a wide variety of point densities depending on the needs of the project. The selection of point density is a big driver of the overall cost of a LiDAR project and should be selected with consideration to the end uses for the LiDAR. Modern LiDAR sensors are capable of acquiring LiDAR data with a higher density than previously available and can do so at higher altitudes and with less overlap. A LiDAR product with 1 point per square meter (ppsm) is sufficient for many applications such as flood mapping in many areas. Higher point densities (4-8 ppsm) allow for greater utilization of the data for mapping planimetric features such as roads and structures as well as for vegetation analysis such as biomass and canopy studies. Additionally, specialized LiDAR at very high densities > 20 ppsm are often used for mapping infrastructure in greater detail such as power lines, pipelines, and for Department of Transportation (DOT) significant features such as mile posts and signs. The ground conditions should be considered when selecting a point density as well. If the area is covered with dense vegetations such as a coniferous forest a higher density and more overlap would be required to penetrate to the ground than an area where leaf-off conditions exist.

(2) Swath Overlap. Planning for swath overlap should also be included in the overall planning of the point density. A higher percentage of overlap may be beneficial in an area with dense vegetation as there will be more look angles from the sensor to the ground at any given points. The result would mean that there could be a lower point density requirement in an individual swath with the overlap accounting for an overall higher point density on the project. Depending on the scanning pattern, data from the extreme edges of the swath may be unusable due to geometric nature of the scan pattern. Typically, 10% overlap between swaths is the minimum requirement for an airborne LIDAR collect. However, most LiDAR flights are conducted with 30% overlap, and those that require higher pulse density in vegetated areas are often flown with 55% overlap.

Q8

b. Flight Planning. Flight planning is always the responsibility of the acquisition contractor. Flight planning for LiDAR will vary greatly depending on the sensor utilized for the acquisition. Parameters such as flying height, ground speed, scan rate, scan angle, etc will be different for each sensor. The contractor's flight plan should be evaluated to ensure there is sufficient swath overlap given the sensor's scanning mechanism and project accuracy specifications. Typically, 10% overlap between swaths is the minimum requirement for an airborne LIDAR collect. However, most LiDAR flights are conducted with 30% overlap, and those that require higher pulse density in vegetated areas are often flown with 55% overlap. A higher percentage of overlap may be beneficial in an area with dense vegetation as there will be more look angles from the sensor to the ground at any given points. The result would be a lower point density requirement in an individual swath with the overlap accounting for an overall higher point density on the project. Depending on the scanning pattern, data from the extreme edges of the swath may be unusable due to geometric nature of the scan pattern. Table 6-1 below shows the operational parameters for a sample LiDAR project for an Optech ALTM 3100 system. The LiDAR flight planning process is mostly automated after entering basic information such as point density, overlap requirements, and scan angles. Trajectories are planned for each flight line. Furthermore, modern Flight Management Systems (FMS) enable the pilot to fly these trajectories with close tolerance. LiDAR sensors are actively acquiring data throughout the entire flight which requires the aircraft to be consistently 'on-line' to ensure full coverage. Additionally, sensor operators are often able to view the acquisition in real time and assess areas where voids or sensor anomalies may be present during the flight. While LiDAR sensors also have some forms of stabilization, the roll, pitch and yaw of the aircraft still depends upon wind conditions. Regardless of sensor to be used, flight planning also includes the assessment of military and other controlled air space where special permits may be required. Aviation Sectional Charts are often used to determine flight restrictions and controlled airspace when planning flight lines.

Table 6-1. Table showing relevant operational parameters for LiDAR data collection.

Item	Parameter
System	Optech ALTM 3100 EA 100 KHz system
Laser Firing Rate	70,000
Altitude (m. AGL)	1,050
Swath Overlap (%)	55
Approximate Ground Speed (knots)	140
Scan Rate (Hz)	37.2
Scan Angle (^{o} ±)	21.5
Computed Along Track Spacing (m)	1.0
Computed Cross Track Spacing (m)	1.0
Average Raw Point Spacing (m)	0.7
Computed Swath Width (m)	827
Number of Flight Lines	379
Line Spacing (m)	372
Maximum Flight Line Length (mi)	64
Laser Beam Divergence	Narrow
Nominal Raw Point Density (pts/m^2)	4

c. <u>Acquisition Planning</u>. With LiDAR sensors it is not necessary to specify standard flying heights as the different sensors each have variable requirements for flying height in order to meet project specifications. The principal flight planning parameters then are the point density and overlap required for the project. With LiDAR sensors, storage is handled via ruggedized mass storage usually in the form of removable hard disk drives or flash drives depending on the sensor in use. Figure 6-7 shows a flight diagram with planned flight lines and cross flight lines that are used for calibration.

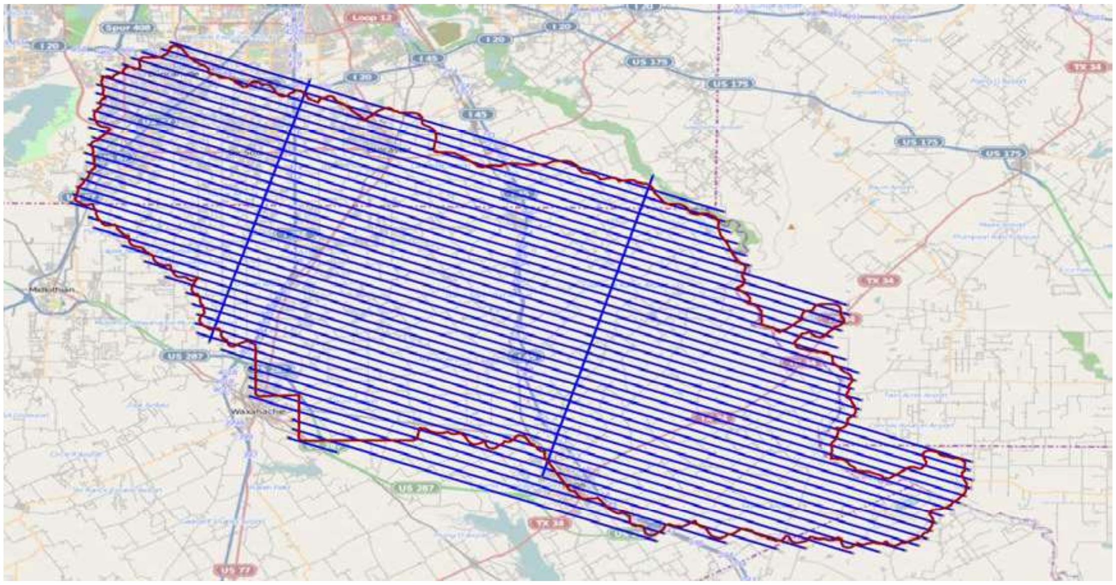

Figure 6-7. LiDAR flight map showing pre-planned flight lines.

Q9

d. <u>Aircraft considerations</u>. USACE shall not specify aircraft to be used for a mapping mission. Twin engine aircraft are used most often for airborne LiDAR remote sensing. Twin engine aircraft provide efficient operations for sensors up to 20,000 feet above sea level; they are equipped with power sources to handle a suite of modern sensors; they offer workspace and comfort to the pilot and camera operator; and the twin engines provide additional safety in the event a single engine should stall. Maintenance, operation, ferry and collection costs can be quite variable among different twin engine aircraft. For altitudes above 20,000 feet, performance (cost) is improved when using turboprop or jet aircraft instead of piston aircraft.

e. <u>Survey Control</u>. Three forms of mapping control support airborne LiDAR mapping: airborne GPS control, ground control, and quality control checkpoints. Contract specifications should reference the following standards and guidelines: FGDC-STD-007.4-2002, Geospatial Positioning Accuracy Standards PART 4: Standards for Architecture, Engineering, Construction (A/E/C) and Facility Management, as well as CHAPTER 3 of this manual, Applications and Accuracy Standards, specifically Table 3-6, Elevation Data Vertical Accuracy Standards. Other references relevant to mapping control include EM 1110-1-1002, Survey Markers and Monumentation; EM 1110-1-1003, Navstar Global Positioning System Surveying; and NOAA Technical Memorandum NOS NGS-58, Guidelines for Establishing GPS-Derived Ellipsoid Heights (Standards: 2 cm and 5 cm), version 4.3.

(1) Airborne GPS Control. Airborne LiDAR is acquired with the use of ABGPS for recording the 3D (X/Y/Z) coordinates of each pulse, plus an inertial measurement unit (IMU) for recording the roll, pitch and yaw of the sensor, when each pulse is transmitted and received (see Figure 6-8). When six exterior orientation parameters of each pulse (X/Y/Z and roll/pitch/yaw) are known, requirements for surveyed ground control are greatly reduced. ABGPS receivers must be capable of tracking both coarse acquisition (C/A) and pseudorange (P-code) data. They must provide dual frequency (L1 and L2) and multi-channel capability with on-the-fly ambiguity resolution and be able to log GPS data at 1-second epochs or better. GLONASS receivers capable of receiving satellite information from GPS and GLONASS constellation are preferred over GPS-only receivers.

Q10

(2) Ground Control. These are the well-established points that GPS ground base stations will be placed on to facilitate accurate positioning of the aircraft In the U.S., this typically involves the use of a Continuously Operating Reference Station (CORS) or the identification and recovery of well-documented permanent control monuments or benchmarks from the National Geodetic Survey's National Spatial Reference System (NSRS) – (go to http://www.ngs.noaa.gov, then click on Survey Mark Datasheets and/or CORS). If a control network of horizontal control monuments and/or vertical control benchmarks does not exist, a control network will first need to be established per references cited above. Figure 6-9 shows an example NGS Data Sheet with the red arrow point at the horizontal and vertical network accuracy at the 95% confidence level. In addition to data shown here, Data Sheets typically also include additional information such as: State Plane and UTM coordinates; U.S. National Grid spatial address; explanations of how horizontal coordinates, ellipsoid heights and orthometric heights were determined; station description and instructions for finding the monument; station recovery history, etc.

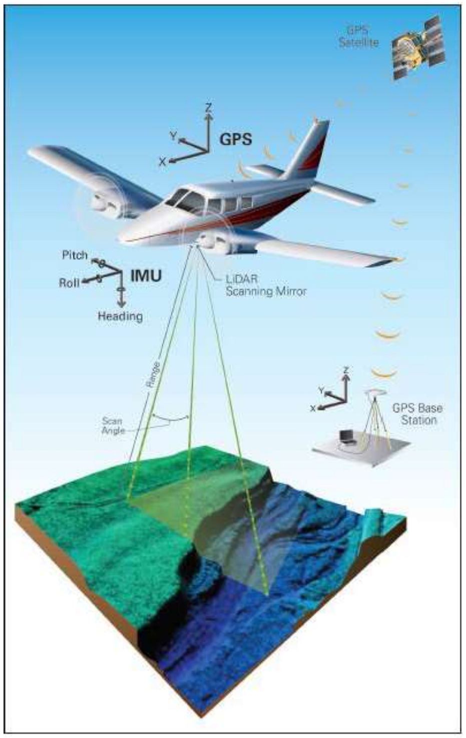

Figure 6-8. Airborne GPS provides x/y/z position of the antenna prior to “lever arm” offset to sensor; IMU provides the roll, pitch and yaw orientation of the LiDAR sensor.

The NGS Data Sheet

See file dsdata.txt for more information about the datasheet.

```
PROGRAM = datasheet95, VERSION = 7.89.3.1
1        National Geodetic Survey,   Retrieval Date = AUGUST 27, 2012
 AJ4599 ***********************************************************************
 AJ4599  HT_MOD       -  This is a Height Modernization Survey Station.
 AJ4599  CBN          -  This is a Cooperative Base Network Control Station.
 AJ4599  DESIGNATION -  FAIRFAX COUNTY EAST
 AJ4599  PID          -  AJ4599
 AJ4599  STATE/COUNTY-  VA/FAIRFAX
 AJ4599  COUNTRY      -  US
 AJ4599  USGS QUAD    -  FALLS CHURCH (1994)
 AJ4599
 AJ4599                        *CURRENT SURVEY CONTROL
 AJ4599  ______________________________________________________________________
 AJ4599* NAD 83(2011) POSITION- 38 55 43.18356(N) 077 08 47.67437(W)   ADJUSTED
 AJ4599* NAD 83(2011) ELLIP HT-    52.373 (meters)        (06/27/12)   ADJUSTED
 AJ4599* NAD 83(2011) EPOCH   -   2010.00
 AJ4599* NAVD 88 ORTHO HEIGHT -     84.26   (meters)      276.4   (feet) GPS OBS
 AJ4599  ______________________________________________________________________
 AJ4599  NAD 83(2011) X  -  1,105,247.067 (meters)                     COMP
 AJ4599  NAD 83(2011) Y  - -4,843,853.080 (meters)                     COMP
 AJ4599  NAD 83(2011) Z  -  3,986,192.174 (meters)                     COMP
 AJ4599  LAPLACE CORR    -          -2.36  (seconds)                   DEFLEC09
 AJ4599  GEOID HEIGHT    -         -31.88  (meters)                    GEOID12
 AJ4599
 AJ4599  FGDC Geospatial Positioning Accuracy Standards (95% confidence, cm)
 AJ4599  Type                                          Horiz  Ellip  Dist(km)
 AJ4599  -------------------------------------------------------------------
 AJ4599  NETWORK                                        0.41   0.98
 AJ4599  -------------------------------------------------------------------
 AJ4599  MEDIAN LOCAL ACCURACY AND DIST (067 points)    0.53   1.22     43.81
 AJ4599  -------------------------------------------------------------------
 AJ4599  NOTE: Click here for information on individual local accuracy
 AJ4599  values and other accuracy information.
```

Figure 6-9. Sample NGS Data Sheet that shows horizontal and vertical network accuracy at the 95% confidence level. Much additional data is also included beyond what is shown.

Q11

(3) Quality Control Check Points. The quality control checkpoints are typically collected by a survey team independent of the LiDAR vendor so that these checkpoints remain “blind” during the LiDAR acquisition and calibration processing. This can be another contracted party or district personnel. The ASPRS Positional Accuracy Standards for Digital Geospatial Data, at Appendix C, provides detailed guidelines on the number and location of check points. Google Earth or other open source imagery can be used for point selection unless alternative orthophotography is available.

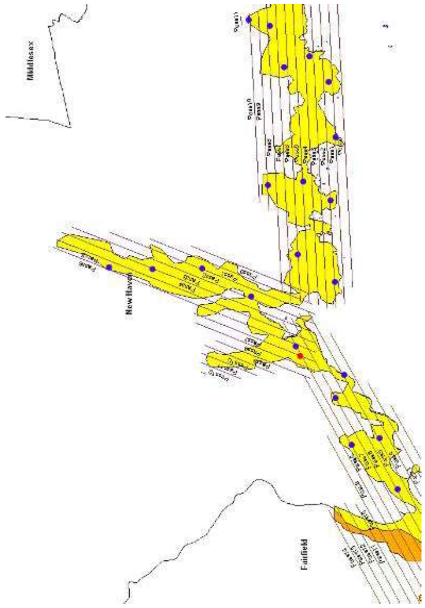

Figure 6-10 - Dispersed Survey, recommended. This shows only a small portion of the county, but the surveyor succeeded in testing many different flight lines. This is most desirable.

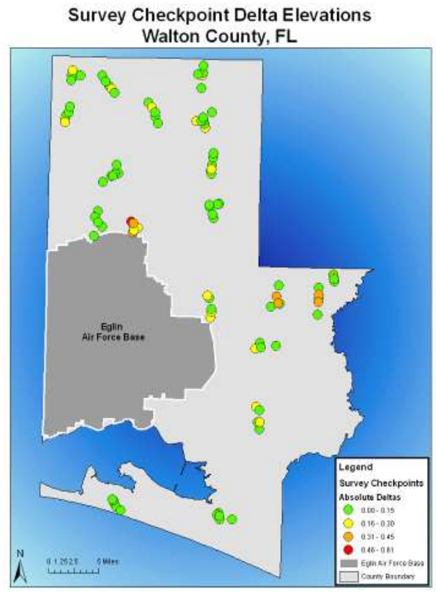

Figure 6-11 - Cluster Survey. For 5 land cover categories, the surveyor attempted to survey one checkpoint in each land cover category from 20 different clusters within the county. Access was originally denied for surveys within the Air Force Base.

(4) Check Point Distribution. When possible, dispersed surveys (Figure 6-10), which provide a more legitimate assessment of data accuracy throughout the project area for different flight lines, are recommended. For dispersed surveys, no two survey checkpoints should be closer than 5,000 feet from the next closest point. If cost and accessibility are an issue, then cluster surveys can be performed (Figure 6-11). Cluster surveys are typically five points when five land cover categories are being tested, one per category, with a minimum spacing of about 1000 feet between points. Clusters should be dispersed following the ASPRS guideline that at least 20% of the points must be in each quadrant. These types of surveys work best with real-time kinematic (RTK) surveys where a base station can be established and five points (all at least 1000 feet apart from each other) can be surveyed. RTK is also ideal for establishing inter-visible pairs for conventional surveys to establish forest points. Please note inter-visible pairs cannot "count" as check points as they typically do not conform to the minimum distance rule. Furthermore, no two checkpoints in a single cluster should be for the same land cover class, and it is often difficult to identify all five land cover classes within the area of a single cluster.

(5) Check Point Location. In addition to land cover classes, location and distribution, the surveyor also needs to avoid known pitfalls in selection of checkpoint locations. It is important for the surveyor to understand that the horizontal coordinates of QA/QC checkpoints do not normally match the horizontal coordinates of individual LiDAR pulses. Instead, LiDAR

elevations are *interpolated* from surrounding points to determine the most probable elevation of the LiDAR data at the horizontal coordinates of each QA/QC checkpoint. Interpolation assumptions are reasonably valid only when the following guidelines are followed with checkpoint selection:

(a) Each checkpoint should be on terrain that is flat or uniformly sloping within 5 meters in all directions from the checkpoint coordinates. Interpolation procedures can fail if the terrain undulates up and down surrounding the checkpoint, or if the slope is curved (concave or convex). Steep slopes should also be avoided for location of checkpoints.

(b) There should be no breakline within 5 meters of a checkpoint. Breaklines define the edge between two intersecting surfaces with different slopes. This rule can best be explained by using a breakline on a bridge abutment as an example of where checkpoints should *not* be located. Interpolation of LiDAR elevations around a bridge abutment would normally include a point on top of the bridge deck and another point over the side of the bridge, perhaps near water level 10 feet lower; interpolating between these two elevations (even if both LiDAR elevations were perfect) would erroneously show that the LiDAR data had an elevation error of 5 feet.

(c) Similarly, checkpoints, even on flat terrain, should avoid logs, tree stumps, rock piles, or other elevated features that could be mapped by LiDAR pulses within 5 meter of a QA/QC checkpoint.

(d) For survey of checkpoints to be used for horizontal accuracy assessments, surveyors should avoid selecting checkpoints with a high probability of being obscured when mapped with LiDAR (or imagery). Because clearly defined point features are required, horizontal checkpoints are commonly surveyed on corners of paint stripes on asphalt. Such points should not be located under trees (in parking lots) for example, because the black/white intensity variations will not be visible. Similarly, such points should not be selected in actual parking spaces where vehicles are liable to be parked at the time the LiDAR data are acquired.

(e) For these reasons, in spite of check point pre-selection, final checkpoint locations cannot be determined in the office but must be left up to the field surveyor. Flexibility must be given to the surveyor as field conditions, including accessibility, are unknown. The surveyor must use the guidance above to plan where checkpoints are likely to be located, but then must make the final decisions in the field, ensuring points are well spaced, have the correct number of land cover categories, and avoid the pitfalls identified above.

6-4. LiDAR Data Processing and Deliverable Development. The range data from the LiDAR sensor are integrated with the aircraft georeferencing (GPS) and orientation (IMU) data to produce a processed laser file, yielding the 3D position and intensity for each laser return. The following sections outline the general steps that are used to process the LiDAR data into some common final deliverables.

a. Data Formatting. After LiDAR acquisition and calibration, LiDAR data are typically processed in order to deliver bare earth classified, LAS files in version 1.2 (formatted to Point Record Format 1) adhering to a specific tiling schema (e.g. US National Tiling Grid) at a specified interval (usually 1,000 m x 1,000 m). Tiles which are fully within the project boundary contain data to the full extent of each tile. Tiles which lie on the project boundary are not filled to the full extent of the tile, unless specified in the scope of work. No over edge data are required but gaps in the data at the project boundary are considered unacceptable. Each LiDAR LAS file (per tile) produced should contain the following elements, as a minimum, for each return:

(1) The return number for each signal

(2) Horizontal and Vertical Position (x,y,z) in the specified horizontal and vertical datum

(3) Intensity return values for each return signal

(4) GPS Timestamp of capture for each point (the timestamp should be unique for each laser pulse)

(5) Georeference information included in the LAS header

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b. LiDAR Data Classification. Classification is the process whereby the acquired LiDAR points are filtered, and those representing ground and above ground features (such as trees and buildings) are assigned to separate classes. LiDAR data can be classified into various categories including ground, vegetation, water body, and buildings. Typically, each LAS file is classified as bare-ground or not bare-ground according to the American Society for Photogrammetry and Remote Sensing (ASPRS) LAS format classification table (at a minimum):

(1) Class 1 – Unclassified (non-ground)

(2) Class 2 – Bare-earth Ground

(3) Class 7 – Noise (low, high or manually identified)

(4) Class 9 – Water (shots from water surface of oceans, lakes, rivers, or streams derived from the breaklines generated from the intensity images)

(5) Class 12 – Overlap

An automated filtering process is first applied where various classes of points are separated. General parameters are set for terrain type (i.e. flat, rolling, hilly) and terrain cover (i.e. open/ non-vegetated, light vegetation, medium vegetation, heavy vegetation), along with other parameters that help fine-tune the automated classification. Vegetation and any other structures are initially separated using an automated process. While the automated classification process often classifies 80% or more of the undesirable above ground features, it also erroneously classifies objects such as natural terrain (hills, rock cuts), or man-made features that should be moved out of the ground Class 2. Therefore, a manual analysis using independent checks is performed to produce the final LiDAR point files. Supplementing automated terrain filtering, LiDAR technicians perform interactive processing to achieve reliable bare earth conditions. The resulting elevation accurately depicts the bare earth surface (Class 2). Class 12 (overlap) is used to classify overlap points that are not used in any other classes. These points are typically along the edge of the scan and are deemed to be unreliable or having poor accuracy and hence not to be used in the ground model. Breakline data are utilized to perform LiDAR classification for class 9 – water (see Section 6.4e). The manual classification is the most time-consuming and often the most expensive component of LiDAR processing. If application of the LiDAR data requires only bare-earth data, there is no need to request for additional classification of buildings, bridges, vegetation, etc. These data will be available in the "Unclassified" class (Class 1) and can be classified in the future if the need for these additional classes arises.

c. LiDAR Data Quality. QA/QC procedures are continued through all iterations of the data processing cycle. Data are typically passed through an automated set of macros for initial cleaning, a first edit by a trained technician, and a second review and edit by an advanced processor, and finally exported to a final product. All final products are reviewed for completeness and correctness before delivery. The goal of LiDAR processing is to achieve the following minimum requirements (or as laid out in the Scope of Work):

(1) LiDAR data from different flight lines will be consistent across flight lines with a maximum 7-10 cm vertical offset between adjacent flight lines. This is referred to as the relative accuracy.

(2) No data voids due to system malfunctions or lack of overlap.

(3) Dense vegetation data voids minimized by automatic removal process.

(4) The lineage (metadata), positional, content (completeness), attribution, and logical consistency accuracies of all digital elevation data produced will conform to the specifications.

(5) Product Accuracy Information Reporting: Product accuracy information will be reported according to NSSDA guidelines. At a minimum, statements concerning source materials and

production processes used will be provided in the metadata sufficient to meet the requirement of the ASPRS Elevation Data Vertical Accuracy Standards (see Chapter 3).

(6) LiDAR data will be classified correctly with limited artifacts or misclassifications remaining in the dataset.

(7) All LiDAR processing and editing will be consistent.

(8) Statistics run on 100% of the data will verify file formatting, projection information, classes used, scan angles, returns per pulse, and nominal point density.

d. LiDAR Data Accuracy. LiDAR data are typically compiled to meet a Horizontal Accuracy of 1 meter RMSE. Bare earth topographic LiDAR data are tested to satisfy Non-vegetated Vertical Accuracy (NVA) and Vegetated Vertical Accuracy (VVA), depending on the Quality Level (QL) chosen. Table 6-2 provides these values as a function of the QL selected when using the USGS Lidar Base Specification Version 1.2 (see Appendix F). VVA will be tested using the 95th percentile for all vegetated land cover categories. LiDAR data are usually tested against a TIN created from the final bare-earth points. Vertical accuracy testing is performed against a TIN as it is unlikely a discrete LiDAR point will be located at the same X/Y location as the survey checkpoints. Note that the NVA and VVA accuracy statistics are affected by bare earth processing, and not necessarily the system calibration.

Table 6.2. Accuracy and Point Spacing for Three Common USGS LiDAR Quality Levels (QL)

Quality Level	$RMSE_Z$ in Non-vegetated Terrain	Non-vegetated Vertical Accuracy (NVA)	Vegetated Vertical Accuracy (VVA)	Nominal Pulse Spacing (NPS)	Nominal Pulse Density (NPD)
QL1	10 cm	19.6 cm	30 cm	0.35 m	8 points/m^2
QL2	10 cm	19.6 cm	30 cm	0.71 m	2 points/m^2
QL3	20 cm	39.2 cm	60 cm	1.41 m	0.5 points/m^2

e. Breaklines. Breaklines assist in the development of hydro-flattened DEMs, if they are required for a project. LiDAR intensity images in combination with the elevation data can be used to create a pseudo stereo pair which then allows a photogrammetric system operator to “see” in 3D and use this technique to better determine the location of ground features. This technique is often defined as lidargrammetry, and is used extensively in the creation of breaklines. The first step is to create synthetic LiDAR stereo-pairs using a software such as the GeoCue LiDAR Pak software. These synthetic LiDAR stereo pairs can then be stereoscopically compiled to create breakline features. SOCET for ArcGIS is often used for this compilation. SOCET for ArcGIS embeds the photogrammetrically-compiled features into an ESRI 10.x geodatabase. This ultimately means there is no CAD to GIS file translation required and that the resultant photo interpreted data is topologically correct and GIS ready upon completion.

Although this requirement is project specific, breaklines are commonly collected for the following features:

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(1) Streams and Rivers. The banks or land/water interface shall be depicted for all linear hydrographic features of a certain width and length (e.g. at least 50 feet in width and ½ mile in length). Islands greater than a certain size (e.g. ½ acre) will be excluded as "holes" in the Streams and Rivers features. Each vertex placed needs to maintain vertical integrity, including monotonicity and connectivity. Exemptions to monotonicity may occur due to complex branch networks. All elevations are at or slightly below the surrounding terrain.

(2) Ponds and Lakes. The land/water interface is depicted for all water bodies, such as lakes, ponds, and reservoirs, at a constant elevation that are usually 1 acre in size or greater. Every vertex on each feature must be placed at the same elevation and all elevation is set at or slightly below the surrounding terrain. Islands greater than ½ acre in size are usually excluded as "holes" in the Ponds and Lakes features.

f. Hydro Flattened DEM Production. The processed and classified LiDAR point cloud may be used to create Digital Elevation Models. For most applications, bare-earth DEMs with 1-meter pixel resolution are created for the project area. These DEMs may be hydro-flattened, using the breaklines collected as described above. The DEMs are tiled according to the project tile grid and are in ESRI GRID format.

g. FGDC Metadata. Project level metadata for each deliverable product must be created. Metadata must be delivered that fully comply with FGDC metadata format standard in eXtensible Markup Language (XML) format. Metadata must contain the following information:

(1) Collection Report detailing mission planning and flight logs

(2) Survey Report detailing the collection of ground control and reference points used for both data calibration and QA/QC accuracy assessments.

(3) Processing Report detailing LiDAR calibration, LiDAR classification, and product generation procedures including methodology used for breakline collection and hydro-flattening.

(4) QA/QC Reports detailing the analysis, accuracy assessment and validation of the point data (absolute, within swath, and between swath); the bare-earth surface (absolute); and other optional deliverables as appropriate

(5) Control and Calibration points: All control and reference points used to calibrate, control, process and validate the LiDAR point data or any derivative products will be delivered.

(6) Geo-referenced, digital spatial representation of the precise extents of each delivered dataset. This should reflect the extents of the actual LiDAR source or derived product data, exclusive of Triangular Irregular Network (TIN) artifacts or raster NODATA areas. A union of tile boundaries or minimum bounding rectangle is not acceptable. ESRI Polygon shapefile is usually preferred.

(7) All metadata files must contain sufficient content to fully detail all procedures used for data processing, QAQC, and finalization.

h. Deliverables. Although users are mostly interested in the final bare-earth DEM from a LiDAR data set, it is important to define a list of deliverables that the vendor will provide from the onset of the survey. A kickoff meeting should be held prior to data acquisition to ensure that all project requirements and schedule are understood. Project partners should be invited to the kickoff meeting. Any concerns from the vendor or the project partners should be discussed during this meeting. Minutes from the meeting should be the first delivery of any LiDAR project. Following mobilization, the vendor must submit daily acquisition and field condition reports that provide an overview of the environment conditions during the time of survey. These reports are usually delivered via email during acquisition, but should be included as a summary in the acquisition report. Following acquisition and upon demobilization, the vendor should prepare an acquisition and calibration report that contains details on the acquisition, tidal considerations (if any), control points used, preliminary vertical accuracy assessment, and all GPS/IMU processing reports for each mission. Figure 6-12 shows a Table of Contents for a sample acquisition report.

Table of Contents

Figure 6-12. Table of contents for a sample LiDAR acquisition report

A LiDAR project report must be delivered at the end of the processing along with the final delivered products. The project report serves as the master report for the entire project and includes detailed explanation on the processing and qualitative assessment performed on the data. The quantitative analysis and the accuracy results (NVA and VVA) must be clearly demonstrated and information on all survey points used for the accuracy analysis must be included. Breakline production procedures should be well defined including the production methodology, qualitative assessment and topology rules used for the project. A data dictionary defining the horizontal and vertical datum, coordinate system and projection used for this project and all breakline feature definitions for streams and rivers, and inland lakes and ponds should be clearly defined. The DEM production methodology and QA/QC assessment on the DEMs must be clearly explained. Often, the LiDAR acquisition report is included in this final project report so that one document provides the complete information on the entire life cycle of the project. Figure 6-13 illustrates a Table of Contents of a sample project report.

Table of Contents

Figure 6-13. Table of contents for a sample LiDAR project report

The list of deliverables must also include the LiDAR data and derivative products as required by the statement of work. Given the very large volume of data, these deliverables are typically requested on external hard drives. The following list of deliverables is usually requested during final delivery:

(1) One set of classified LAS files in accordance with the tiling schema noted in the statement of work.

(2) One set of raster DEM's (hydro flattened bare earth) delivered in the specified grid format (for e.g., GeoTIFF or ESRI Raster Grid). The DEM's must also be delivered in the project tiling and required naming schema.

(3) One set of 1-meter intensity imagery in GeoTIFF file format.

(4) One set of FGDC Metadata for each data deliverable.

(5) One ESRI file geodatabase containing the breakline data, if specified.

(6) Project report

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CHAPTER 7
Airborne Bathymetric LiDAR

Q14

7-1. Background. Airborne LiDAR Bathymetry (ALB) is a mature surveying and mapping technology that uses blue-green laser pulses fired from low-altitude aircraft to measure underwater elevations in moderately clear, near-shore coastal waters, shallow rivers and lakes (Guenther, 2007). Although early developments in ALB were driven by the hydrographic surveying community for the production of nautical charts, today ALB is used for a variety of engineering and environmental applications in the coastal zone.

a. USACE has operated ALB sensors for engineering applications since 1994 (Lillycrop et al. 1996). Based on the intervening 20 years of operations, ALB has proven to be an accurate, cost-effective, rapid, safe, and flexible method for surveying in shallow water and near coastlines where sonar systems are less efficient and can even be dangerous to operate (LaRocque and West, 1999; Wellington, 2001; Skogvik and Axelson, 2001). Applications for the data have expanded from project scale surveys of navigation channels and coastal flood risk reduction projects (Irish et al. 1995), to regional scale surveys that support watershed management of projects and post-storm damage assessment (Wozencraft and Millar, 2005). More recently, extraction of key geomorphological parameters, indexes for insfratructure assessment, and fusion of ALB with hyperspectral imagery for environmental applications like invasive species, wetland, and submerged aquatic vegetation mapping (Reif et al. 2012) have provided a mechanism by which to quantify the coastal zone in engineering and environmental terms.

Q15

b. The primary user of ALB technology in USACE is the National Coastal Mapping Program (NCMP). The NCMP is the only Federal coastal mapping program that collects data for the entire U.S. coast, one region per year, with a repeat cycle of five years (Wozencraft and Lillycrop, 2006). The NCMP collects high-resolution bathymetry, topography, and imagery data to support regional sediment management for the USACE Navigation Business Line (Figure 7-1). These data are also broadly applicable to watershed and project management for the Flood and Coastal, Environmental Stewardship, Emergency Management, and Regulatory Business Lines. The NCMP has been the driver behind ALB sensor, data processing, and derived data product development in USACE since 2004 (Wozencraft, 2010). Surveying and mapping requirements for USACE projects are also being met with ALB sensors, and are often performed in conjunction with the NCMP.

Figure 7-1. Example of bathymetry and topography collected with an ALB sensor for the National Coastal Mapping Program at Seabrook Harbor in New Hampshire.

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7-2. Technology Overview.

a. The ALB technique relies on propagation of blue-green laser pulses through the water to reflect from the seabed, and then to make the return trip back through the water to receivers in the aircraft. Figure 7-2 (a) depicts all the interactions of the laser pulse with the water, including a specular interface reflection, forward scattering of the light through the water column, volume backscatter by particles in the water column as well as water molecules themselves, absorption by particles in the water column, and finally a diffuse bottom reflection (Guenther, 1985). Figure 7-2 (b) depicts the LiDAR signal, or" waveform" that is received and recorded by the ALB sensor, and then analyzed by sophisticated algorithms to result in an accurate water depth measurement. These scattering and absorption properties of the water column are the primary limitation for ALB sensors. If the water is too turbid, or has a high fraction of suspended sediments, bubbles, or organic material, the volume backscatter will be greater than the bottom return and no depth can be determined. While water turbidity determines whether a depth can be measured, detection of the sea surface determines whether an accurate depth can be measured (Guenther, 2000).

b. There are several ALB sensors available in the marketplace today. The Coastal Zone Mapping and Imaging LiDAR (Tuell et al. 2010, Figure 7-3) was developed by Optech for the JALBTCX program and leveraged experience gained in developing and operating the SHOALS (Lillycrop and Banic, 1993) and CHARTS (Lillycrop et al., 2002) systems. These systems were developed to support engineering applications in USACE, but are widely used by the Naval Oceanographic Office for nautical charting surveys. The Airborne Hydrography AV (AHAB) HawkEye III (includes Chiroptera) and Fugro LADS-MK III followed similar development paths in Sweden and Australia for nautical charting applications. These systems all have a 20 year operational heritage of producing accurate surveying, mapping, and charting data. In recent years, since about 2011, the Riegl V800G series and the Optech Aquarius/Titan sensors have

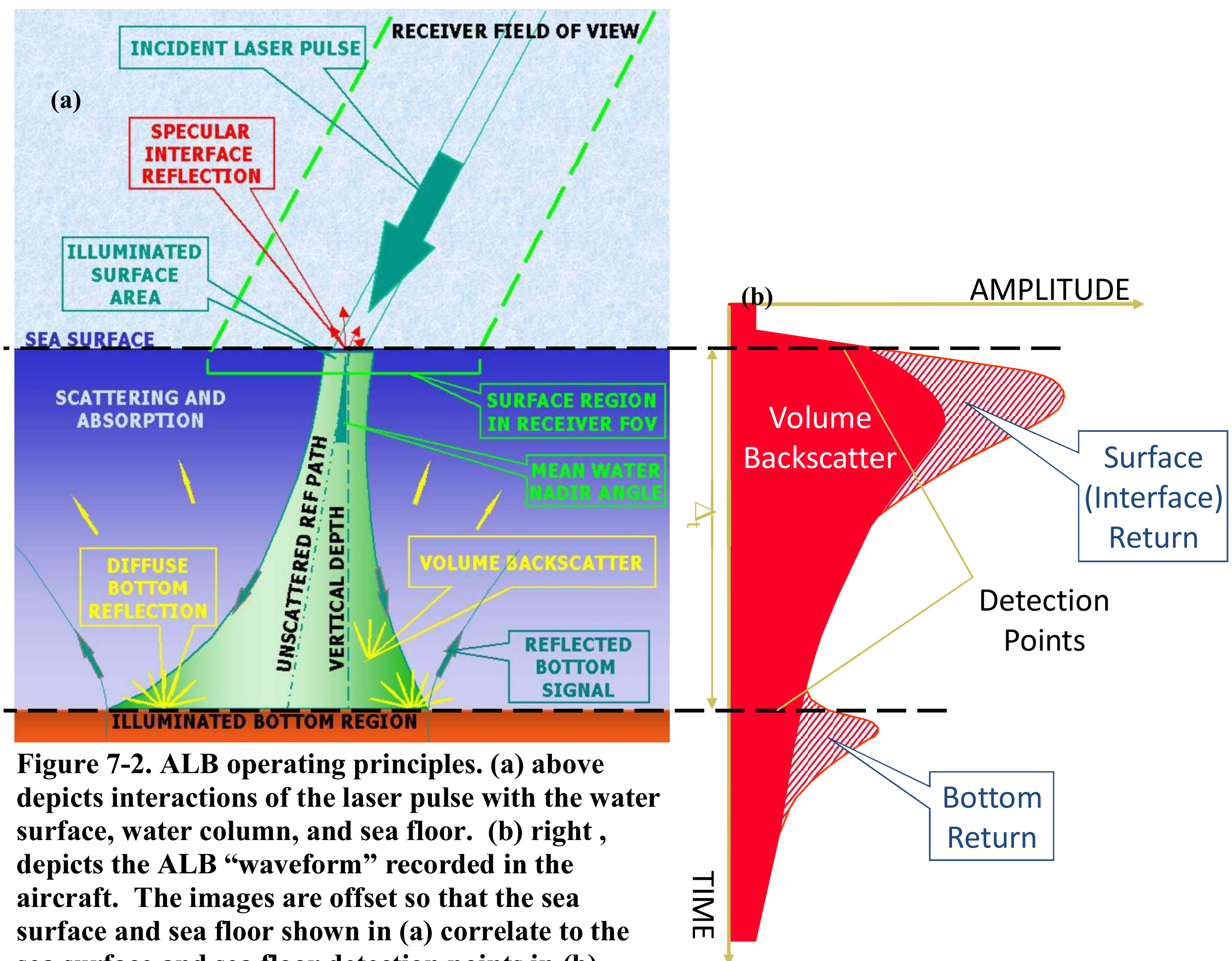


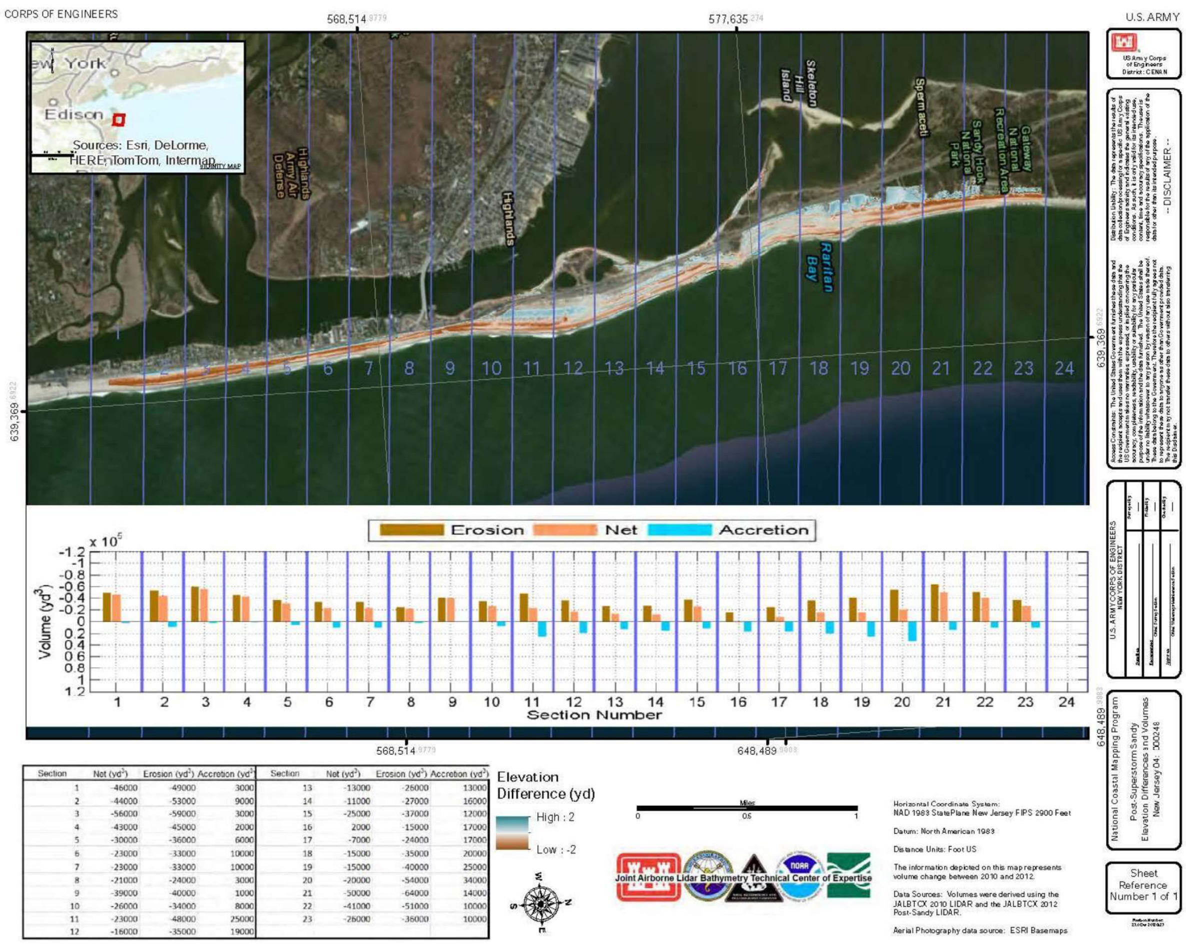
Figure 7-2. ALB operating principles. (a) above depicts interactions of the laser pulse with the water surface, water column, and sea floor. (b) right , depicts the ALB "waveform" recorded in the aircraft. The images are offset so that the sea surface and sea floor shown in (a) correlate to the sea surface and sea floor detection points in (b).

emerged from the topographic LiDAR community. These are generally referred to as "topo-bathy" sensors in that they are primarily topographic LiDAR sensors and have a limited bathymetric capability since they operate at blue-green wavelengths.

7-3. Planning an ALB Project. Successful ALB surveys require an in-depth understanding of the sensor technology and its operational limitations, sophisticated processing algorithms that provide accurate depth measurements regardless of environmental conditions like the sea surface, sea floor, and water column, and a broad understanding of both topographic and hydrographic surveying and mapping.

a. Joint Airborne LiDAR Bathymetry Technical Center of Expertise (JALBTCX) is a resource in USACE that can help with many aspects of ALB and coastal surveying and mapping project planning, execution, data processing, exploitation, and dissemination. JALBTCX has in-house capability to perform ALB surveys on a reimbursable basis using the state-of-the-art in ALB survey technology designed by USACE for USACE engineering and environmental applications, as well as contract capability through an indefinite delivery, indefinite quantity contracts for airborne coastal surveying and mapping. USACE and its partners in JALBTCX, the Naval Oceanographic Office, the National Oceanic and Atmospheric Administration, and the U.S. Geological Survey, have operational experience with all of the ALB sensors currently in operation, and with all ALB service providers, and communicate regularly on ongoing ALB surveys. JALBTCX can also provide services including development of scopes of work, quality assurance/quality control procedures, flight plans, independent government estimates, deliverable product specifications and evaluation, metadata specifications, and general information about airborne LiDAR bathymetry/topography and hyperspectral imager technology. JALBTCX develop value-added products from raw, high-resolution elevation/depth and imagery data, like extraction of geomorphological and environmental features of interest from high-resolution regional datasets by fusing LiDAR with hyperspectral imagery, and comparing repeat datasets to quantify changes for a survey area. You can contact JALBTCX at JALBTCX@usace.army.mil or 228-252-1131.

b. JALBTCX has capability and capacity to perform regional airborne coastal surveys, and deliver data in 24 hours in response to regional scale emergencies. JALBTCX has responded to hurricanes since Hurricane Opal 1995 providing surveying and mapping and damage assessments (Irish et al., 1996; Wozencraft and Millar, 2005; Wozencraft and Lillycrop, 2006; Reif et al., 2011a, Wozencraft 2012). JALBTCX is a coordinating organization for all regional coastal mapping with contacts in government and industry to ensure the USACE leverages other coastal mapping activities to the greatest extent possible considering the accuracy of data required by USACE. JALBTCX also has access to pre-event data for the coast of the US and has developed quick turn-around change detection products in collaboration with coastal engineers to quantify change due to coastal events (Figure 7-3).



Section	Net (yd^3)	Erosion (yd^3)	Accretion (yd^3)	Section	Net (yd^3)	Erosion (yd^3)	Accretion (yd^3)
1	-46000	-49000	3000	13	-13000	-26000	13000
2	-44000	-53000	9000	14	-11000	-27000	16000
3	-56000	-59000	3000	15	-25000	-37000	12000
4	-43000	-45000	2000	16	2000	-15000	17000
5	-30000	-36000	6000	17	-7000	-24000	17000
6	-23000	-33000	10000	18	-15000	-35000	20000
7	-23000	-33000	10000	19	-15000	-40000	25000
8	-21000	-24000	3000	20	-20000	-54000	34000
9	-39000	-40000	1000	21	-50000	-64000	14000
10	-26000	-34000	8000	22	-41000	-51000	10000
11	-23000	-48000	25000	23	-26000	-36000	10000
12	-16000	-35000	19000				

Figure 7-3. Volume change map developed in collaboration with coastal engineers in the aftermath of Hurricane Sandy. This product can be generated within 48 hour after data collection with JALBTCX automated algorithms.

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c. Define the survey area and intent. A discussion about an ALB survey project begins with an outline of the desired survey area. ESRI shapefiles, Google Earth kml/kmz files, web-based collaboration tools, or even hand-drawn boxes on a map or aerial photo are effective means of providing this information. The flight time required to cover the survey area is one of the major cost drivers for any airborne survey, and ALB is no exception. A common mistake is to draw a very general box or outline, and then find out the cost of the survey, and then go through iterations to get to the final survey area. Though some iteration is expected, starting with a more specific outline of the survey area will reduce the amount of time required to finalize the survey area. A key point to remember is that each flightline, or pass of an ALB sensor, will cover an area about 300 m (1000 ft) wide under the aircraft at the nominal flying altitude, so that is the level of granularity the project outline can accommodate. A brief description of the intended use of the final data set is also valuable information and may shape some unexpected aspects of the data collection.

d. Determine the schedule. Several factors will determine when an ALB survey will be performed, primary among them weather, water turbidity, ALB sensor availability, mobilization costs, and airspace restrictions. Best practice is to start discussion early, as soon as ALB is considered to meet project survey requirements. This will ensure quality data are collected and available when needed, and can result in significantly reduced cost for the project.

(1) Weather. Knowledge of general weather patterns for the project area can help identify the optimal time for aircraft operations. Frequency of low pressure storm systems, and daily patterns like afternoon thunderstorms, fog, and marine layers can all impact aircraft operations. Targeting times of the year when these are lowest decreases overall risk of the project, and therefore reduces cost.

Q18

(2) Turbidity. The single most important consideration for success of an ALB survey project is turbidity, or the amount of suspended sediment and organics in the water column. If the water has a high content of sediment and/or organic particles, the photons in each laser pulse will be scattered and/or absorbed to such an extent that an insufficient amount of light returns to receivers in the aircraft to make an accurate depth determination. Local knowledge of turbidity and its drivers in the survey area is key to scheduling an ALB survey for the greatest chance of success. Answers to the following questions help determine the best time to perform an ALB survey:

(a) When is the water clearest?

(b) What time of year has the lowest winds? Does a certain wind direction increase /decrease suspended sediments in the water?

(c) What time of year has the lowest waves, both wind waves and swell?

(d) What time of year has lowest rainfall?

(e) Are algal blooms a concern? At what time of year?

(f) When does submerged aquatic vegetation have the highest biomass?

(g) What time of year is river discharge lowest?

(h) When is tide range the largest, or when are spring and neap tides?

(i) In areas impacted by riverine discharge, do incoming tides push cleaner water nearshore?

(j) For river surveys, what water levels and flow conditions result in clearest water?

(k) Can river flow be controlled to improve water clarity?

(l) What time of year are runoff from rivers, river discharge volumes, effect of flooding and farming activities lowest?

(m) Are there ongoing O&M or Construction activities that impact water clarity, like channel dredging or sand placement in the nearshore?

(3) Availability of ALB sensors. Though ALB technology is not new, the entry cost and operational risk of the ALB market are high. As a result, there are not many systems available to perform survey work. JALBTCX owns and operates ALB sensors. Commercial surveying and mapping companies own and operate ALB sensors, but these are often engaged in prolonged nautical charting surveys overseas. Other less experienced surveying and mapping companies have access to systems that they rent from ALB sensor manufacturers. Providers with airborne coastal mapping and charting experience that have well-established standard operating procedures and processing pipelines are lowest risk in terms of cost, schedule, and data quality.

(4) Mobilization cost. For a typical project-scale survey, the cost of mobilizing the ALB sensor and crew to the survey area is often higher than the cost of the ALB survey. To reduce cost of mobilization, it is advantageous to leverage other ALB surveys that may be planned in

the area. For example, if a survey requirement aligns with the USACE NCMP schedule, JALBTCX can add the project area to their schedule with little mobilization cost. Or, if several survey requirements in a geographic area can be combined into a single survey effort, the mobilization cost can be shared among the requiring projects.

(5) Airspace restrictions. Survey areas near large airports, military bases and power plants may require coordination in advance of airborne operations. Designated wildlife and sanctuary areas also often require permits for aircraft operations. Managers of these areas should be included early in the discussions to ensure aircraft operations are permitted and occur according to the defined survey schedule. Finally, it is always best practice to engage and inform the Public Affairs Office (PAO) in the District in which the survey will occur, as low-flying aircraft occasionally excite the general public. ALB operations can occur in the day or night which can help in navigating through some airspace restrictions and the District PAO should consider informing local officials and the public as the green laser is visible in the night from the aircraft.

7-4. Specify the Acquisition Requirements. It is important to specify the acquisition requirements for a typical ALB survey such as required reference datums, accuracy, and whether ancillary data (topographic LiDAR, aerial photography, hyperspectral imagery) are required. The acquisition requirements must also specify the reference data that will be used to perform QA/QC and validate the accuracy of the ALB data. The following sections include recommended acquisition requirements for ALB surveys.

a. Reference Datums.

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(1) Horizontal Control Datum. Control monuments used shall be tied to NAD83 (NSRS 2011, or the newest realization of the NAD83 ellipsoid if superseded) and established through accepted surveying and mapping techniques. Refer to USACE EM -1110-1-1005, Control and Topographic Surveying for further guidance.

(2) Vertical Control Datum. Control monuments used will be referenced to the newest NGS National Adjustment of the National Spatial Reference System, currently NAD 83(2011, PA11, MA11). Refer to USACE EM -1110-1-1005, Control and Topographic Surveying for further guidance.

b. Nominal pulse spacing. Nominal pulse spacing is the distance between LiDAR measurements. ALB nominal pulse spacing ranges from around 25 cm (16 points per square meter) in shallow water to 5 m (0.04 points per square meter) in deep water. ALB point spacing is highly dependent on the sensor used for data collection, and has a reciprocal relationship with depth performance of the ALB system. That is, ALB sensors with the smallest pulse spacing are only able to operate in very clear, calm water. Unless the survey area meets these conditions, the recommend nominal pulse spacing is 2 m (0.25 points per square meter).

c. Accuracy. The physical survey environment and ALB system hardware present challenges impacting accuracy of the final survey product. These must be appropriately addressed through thoughtful hardware and software system design and construction, as well as the prediction, modeling, and application of appropriate correctors for various sensor and environmental parameters (Guenther 1985, Guenther 2000).

(1) Vertical Accuracy. Field tests of USACE systems, formal comparisons to datasets of opportunity, and 20 years of internal and external comparisons to ground truth and other datasets have established the accuracy of data from well-designed, appropriately operated ALB sensors processed with sufficient calibration parameters to be 15 cm RMSE (Lillycrop et al., 1994; Riley, 1995; Irish et al, 2000; LaRocque, 2004; Wozencraft and Lillycrop, 2006), which meets the accuracy requirements for many USACE activities enumerated in Table 3-17. Newer ALB sensors are made with lasers that produce shorter laser pulses than have been available in the past. These systems are theoretically and anecdotally capable of better accuracies, but there is no comprehensive assessment of this capability to date. The International Hydrographic Organization Standards for Hydrographic Surveying (S-44, IHO 2008) is commonly used as an accuracy standard for ALB surveys for nautical charting. The USACE vertical accuracy standard for hydrographic surveying is tighter than accuracies required by this standard. The recommended vertical accuracy acquisition requirement remains 15 cm RMSE.

Q20

(2) Horizontal Accuracy. The location of the laser footprint on the water surface with respect to the aircraft location is known with very high accuracy and is typically less than 20 cm RMSE in a well-designed system. The effective location of the submerged surface mapped by a laser beam is much more complex to determine because it is subject to uncertainties related to the water surface waves, the effect of water clarity on the beam propagation through the water column, and the shape and reflectivity of the submerged surface or object being mapped, the footprint of the transmitted laser pulse and the receiver field-of-view. Surface waves can increase the horizontal error of the submerged surface when the size of the laser footprint on the water surface is small compared to the wavelength of the surface waves. Given all of these

considerations, and consistent with results of field tests designed to specifically test it (LaRocque, 2004), the recommended horizontal accuracy for ALB is 1.5 m RMSEr.

d. Topographic Survey Requirements. Most ALB sensors have been equipped with capability to collect land elevations concurrent with water depths since the late 1990's. With the exception of nautical charting surveys in open water, it is rare that ALB is utilized to collect only bathymetry data. It is far more common that ALB surveys have a topographic component that captures upland beaches and coastal structures along with bathymetry. This is done by analyzing the ALB returns to determine topography, or by adding a stand-alone topographic laser system to the ALB sensor platform. Using either approach, there is no constraint on how far inland ALB sensors may be used to capture topography. The topographic LiDAR should always be acquired simultaneously with the ALB data to minimize temporal discontinuities between the topographic and bathymetric data.

(1) It is appropriate to use the guidelines presented in Chapter 6 Airborne Topographic LiDAR, when defining acquisition requirements for topographic data collection associated with
Q21 ALB surveys. The major difference between traditional topographic LiDAR and topographic data collected by ALB sensors is laser footprint size and flying height. Because of eye safety requirements, ALB sensors spread laser energy over a larger ground footprint, so ALB topography measurement represents a 50-70 cm area on the ground. ALB sensors are flown lower than topographic LiDARs, usually between 300 and 600 m. The lower flying height may
Q22 result in "shadows" in the topography data for some scanner types. The acquisition requirement should address whether shadows in the lee of trees and buildings relative to the flight direction are acceptable for non-circular scanners.

(2) Recommended vertical accuracy for topographic data collected by ALB sensors is 10 cm RMSEz. Recommended horizontal positional accuracy is 0.5 m RMSEr.

e. Aerial Photography Requirements. Most ALB sensors have integrated aerial cameras to provide down-looking images that are used during data processing, but that are also valuable as deliverables. It is appropriate to use the guidelines presented in Chapter 4 Aerial Photogrammetry when defining acquisition requirements for aerial photography collection associated with ALB surveys. Because of the low flying height, more images will be collected to cover the survey area, but the resolution will be very high, on the order of 5 cm. The imagery is collected at the time of LiDAR data collection, so solar and atmospheric conditions may not be ideal for imagery collection. Airspace restrictions, that require night survey operations, may preclude concurrent imagery collection with the LiDAR. If high-quality imagery is required, this should be clearly defined in the acquisition requirements so that a separate flight may be planned under the appropriate conditions at additional cost to the survey project. Processing of imagery collected with ALB sensor data is typically done using direct geo-referencing rather than aero-triangulation techniques.

f. Hyperspectral Imagery Requirements. Data fusion techniques, combing LiDAR and hyperspectral imagery, can be used for a variety of applications including bottom classification of sand, coral, hardbottom, and mud, water column composition, discriminating submerged vegetation, identifying invasive species, and quantifying landcover like vegetation on dunes and impervious surfaces (Park et al., 2010; Reif et al., 2012; Wozencraft and Park, 2013).

(1) Recommended acquisition requirements are 1m ground sampling distance (pixel size) and 48 spectral bands evenly between 375 and 1050 nm.

(2) Like aerial photography, solar and atmospheric conditions during LiDAR collection may not be optimal for hyperspectral imagery collection, so an additional flight may be required under optimal image acquisition conditions. To reduce shadows in hyperspectral imagery on land, it is best to fly within 3 hours of solar noon. For water applications, solar zenith angle should be between 20 and 50 degrees to ensure there is enough illumination in the water column, but also avoids sun glint. For applications that seek to constrain hyperspectral image processing with water column information from the ALB sensor, such as for water quality studies (Reif et al., 2011b), it is necessary to collect the ALB data and hyperspectral imagery simultaneously at the most optimal conditions for both sensors.

g. ALB Cross Lines. ALB cross lines are lines flown perpendicular to the production flightlines, usually in the onshore-offshore direction. These lines are collected on a different day from the production lines and are used to verify internal consistency of the ALB data. For QA/QC purposes, one cross line should be collected when multiple flights are required to cover the full depth range in the survey area. Elevation ground truth areas (described below) should also be captured by cross lines.

h. Elevation ground truth. In addition to ALB cross lines to test the internal consistency, or precision of the data, ground truth data are collected on land to verify absolute accuracy.

(1) The ground truth data are collected using a survey technique that is an order of magnitude more accurate than the airborne data collection. These should be collected on both bare ground and in vegetation that is representative of the survey area. Ground truth data collected in vegetated areas tests both the capability of the ALB sensor to penetrate vegetation, and the capability of the ALB data processing to identify bare ground points.

(2) For regional alongshore data collection projects, establishing ground truth locations such that each point collected by the ALB sensor falls within 50 miles of a ground truth site is recommended. Ground truth location should be sited on flat or uniformly sloping ground with less than a 20 percent grade.

i. Spectral ground truth. To assist in evaluating the quality of hyperspectral imagery and its atmospheric correction, two (2) spectrometer observations shall be made over pseudo-invariant features at locations no more than 100 miles apart. For some environmental applications such as submerged aquatic species discrimination (Reif et al. 2011c), invasive species mapping, and other species level vegetation and water quality mapping, additional spectral ground truth measurements may be required.

j. ALB Performance. Another best practice for ALB surveys is to clearly state in the scope of work how to address those parts of the survey area where ALB may not be able to determine a water depth. These areas are typically near the shoreline where breaking waves and entrained sediment keep the laser light from penetrating to the seafloor, in areas with persistent turbidity such as with a river plume, and, in some cases, in areas with low bottom reflectivity.

(1) Most of these scenarios can be overcome through operational techniques, like flying at both high and low tide, or revisiting the site on different days when water conditions are different. In all cases these techniques require additional flight time, which is the primary cost driver for ALB surveys. Special consideration should be given to those areas where data must be acquired, and where allowances might be made for limitations of the technology given the additional cost associated with overcoming those limitations.

(2) Performance of the bathymetric portion of this task order should always be on the 'best level of effort' criteria, with optional allowance made for some percentage of reflown flightlines, additional standby days, or multiple attempts over the survey area.

k. Other relevant USACE Guidance. Concurrent and ancillary data collection shall comply with relevant Engineer Manuals and other USACE guidance. These include but are not limited to USACE EM -1110-1-1002, Survey Markers and Monumentation; USACE EM -1110-1-1003, NAVSTAR Global Positioning System Surveying; USACE EM -1110-1-1005, Control and Topographic Surveying; USACE EM -1110-2-1003, Hydrographic Surveying; and USACE EM -1110-1-2909, Geospatial Data and Systems.

7-5. Define the Deliverables. There are many deliverables that can be generated from ALB data and simultaneously-collected sensor data. The most basic is a LiDAR point cloud in which points on bare ground are identified. Derived data products include Digital Surface Models (DSMs) Digital Elevation Models (DEMs), LiDAR reflectance images, shorelines, and aerial photo and hyperspectral image mosaics. These deliverables are generated using automated processes and add little extra cost to the project. More advanced deliverables like landcover and benthic classification, elevation and volume change comparisons to previous data. The Report of Survey deliverable contains a summary of the survey activity and results of QA/QC performed as part of the project. The following sections outline recommended specifications for the most common ALB survey project deliverables.

a. Coordinate System and Vertical Reference. Specify the desired coordinate system, whether geographic or projected, like UTM or State Plane with the appropriate zone, and units of meters or feet. The vertical reference should be defined such as NAVD88 or the appropriate water level reference such as MSL, along with desired units. For areas where water level reference cannot be determined through VDatum, an offset between NAVD88 and the water level reference must be applied. The value applied and methodology to apply that value should be defined considering the use of the final delivered data.

b. Tiling of deliverables. If the project area is large, larger than a few tens of square kilometers, it may be wise to specify a tiling scheme. This can be provided in shapefile format, if there are specific project-related boundaries that can be used to delineate the larger survey area. Existing tiling scheme may also be used, for example, the NCMP has historically used 5 km alongshore boxes for data delivery, or the USGS digital ortho quarter quarter-quad boundaries.

c. Classified Point Data in LAS Format**.** LAS is the industry-standard format for exchange of LiDAR point cloud data. ALB data shall be classified in accordance with ASPRS categories. LAS is a widely interpreted format, and updating of tools that ingest LAS data often lag LAS version updates. Care should be taken to specify the LAS format version and attributes such that the delivered LAS files are compatible with the software available to read them. LAS v1.2 is the current widely adopted version. At a minimum, under this version include categories 1 and 2, and an agreed upon category for bathymetric data returns. Classification value 1 distinguishes points that have been processed through an algorithm but not identified as a ground shot. Classification value 2 shall be assigned to all points representing ground returns. JALBTCX uses category 29 for bathymetric LiDAR returns. When the newly published LAS v1.4 becomes more widely adopted, a subset of the Topo/Bathy Lidar Domain Profile should be used (Table 7-1). All valid data collected during production flight lines shall be processed and used to generate the final products. This includes data that are collected outside of the project boundary specified in the scope. Metadata in an FGDC-endorsed format shall be provided per collection of LAS files.

Table 7-1. LAS format LiDAR classification scheme for topobathymetric data

LiDAR Classification – Final Deliverables	
Class	**Description**
Class 1	Unclassified
Class 2	Ground (Topo)
Class 40	Bathymetric point (e.g., seafloor or riverbed; also known as submerged topography)

d. DEM Specifications. Two elevation models are recommended deliverables, one of all the valid data and one of the bare ground identified points. The first, a DSM, will include all vegetation, buildings, other ground features and bathymetry. The second, a DEM, represents ground topography and bathymetry without these features. An example DSM and DEM from the Lake Ontario shoreline are shown in Figure 7-4. The DEMs shall be provided as elevation rasters in 32-bit geo-tiff format. The raster will have 1-meter pixel resolution with the lower-left corner as the reference point. The elevation of each grid cell should be interpolated from a TIN surface of the data points. Interpolation across data gaps will not exceed 10 meters and elevations will not interpolated more than 5m away from actual data points. The exception would be for data gaps resulting from the removal of buildings where full interpolation across the data gap is required. In areas of no data, the raster cells will be assigned an elevation value of 'No Data'. The raster will be created such that the edges of adjacent tiles have matching elevations. Further, the origin point of the DEM should be evenly-divisible by the DEM resolution, such that cell boundaries for subsequent surveys will align. DEMs are generally used in ArcGIS. When the raster is loaded into ArcGIS, the elevation range for the tile shall be indicative of the actual

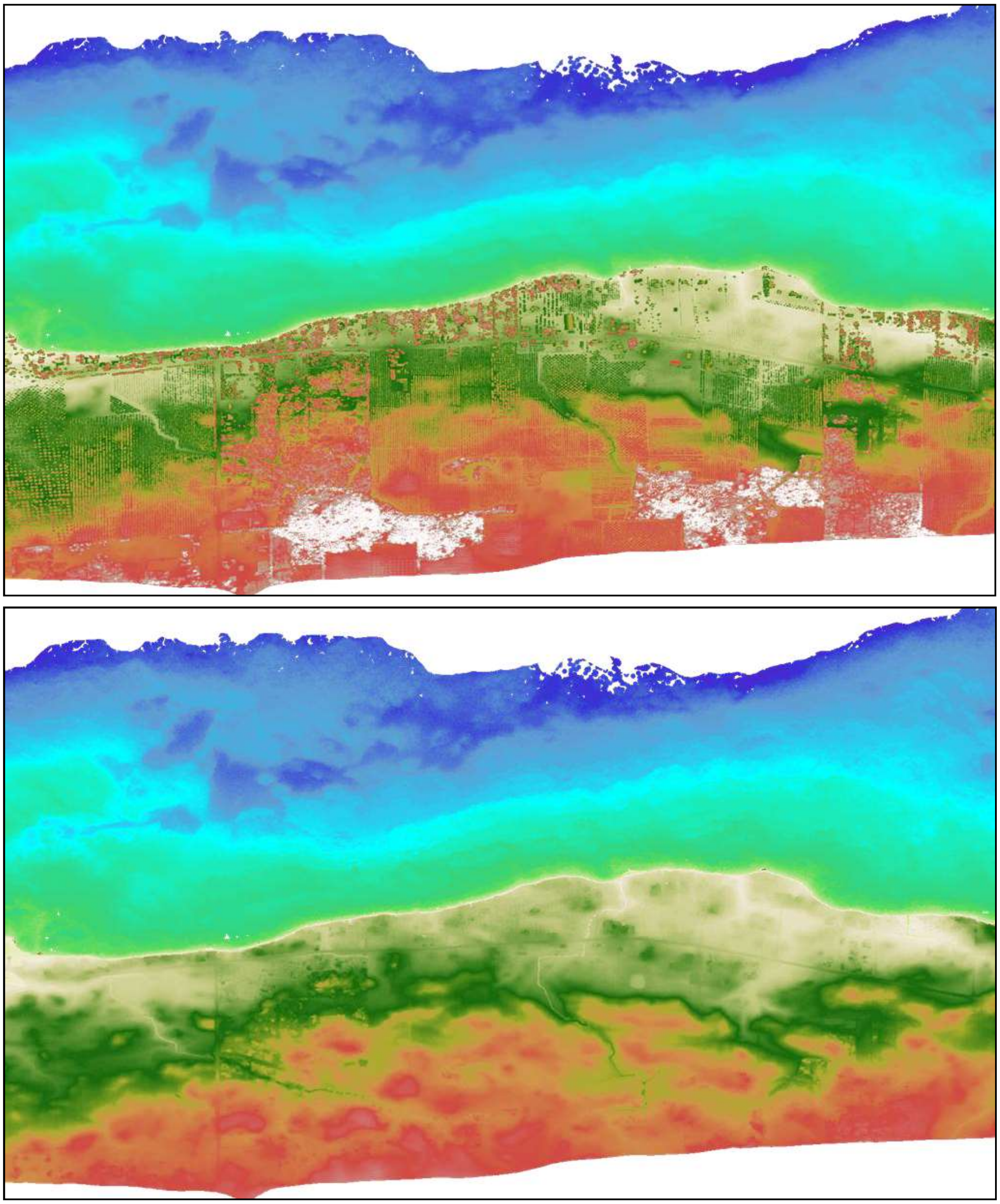

Figure 7-4. Example digital elevation models from the shoreline of Lake Ontario. In both the top and bottom panels, land is at the bottom of the image and water is at the top. The top panel is a DSM that include trees and building in the elevation model. The bottom panel is a DEM, where those and other above ground features have been removed, and only bare ground remains. Bathymetry is included in both elevation models.

values observed in the data. There should be no gaps or overlaps between adjacent grids. Metadata in an FGDC-endorsed format shall be provided per geo-tiff.

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e. Aerial Photography. Orthomosaics at 25 cm (1-ft) resolution are the recommended deliverable for aerial photography. Images over navigation structures and other features of interest may be specified for a 5 cm-resolutin product. The LiDAR elevation data is the best elevation source for creation of the orthosmosaics. The orthomosaics shall be provided in GeoTIFF format and referenced to the coordinate system and vertical reference for the project. Metadata in an FGDC-endorsed format shall be provided per orthomosaic.

f. Reflectance Images**.** Laser reflectance images are gray-scale images of the survey area at the laser wavelength of 532 nm. The topographic analog of this project is an intensity image. If the ALB sensor is radiometrically calibrated, the value of each pixel is the absolute reflectivitiy of the object. If the ALB sensor is not radiometrically corrected, the reflectance values are called pseudo-reflectance (Wozencraft and Park, 2013). The laser reflectance image shall be generated at the resolution of the LiDAR data. Values for the image shall range from 0 to 1, with 0 representing total absorption and 1 representing total reflection. The image shall be provided in GeoTIFF format. Metadata in an FGDC-endorsed format shall be provided per reflectance image.

g. Hyperspectral Imagery**.** Hyperspectral image strips shall be processed into 1-m resolution at-sensor radiance mosaics using sensor-specific lens and radiometric correction files. The images may be further corrected to reflectance images using atmospheric correction techniques. Formats vary for hyperspectral imagery, so be sure to specify a format that can be read with software available to the end users. The coordinate system is typically the appropriate UTM zone for the survey area. Metadata in an FGDC-endorsed format shall be provided.

h. Report of Survey**.** The Report of Survey provides documentation of the survey processes, procedures, collection conditions, and results of the QA/QC tests of the data. The report should include, at a minimum, airborne collection logs, calibration reports, accuracy check reports, daily reports, GPS logs, NGS control sheets, photos of control points, processing logs, list delivered files, description of survey, dates of collection, and a list of problems encountered. Full documentation of all control used, existing or established, shall also be provided in the Report of Survey. Because QA/QC tests are the basis for evaluating the final quality of the ALB data collection, processing, and product generation, for acceptance, recommended tests are described below. Procedures for and results of testing should be included in the Report of Survey.

(1) Calibration Report. The calibration report should describe lab and flight calibrations of the ALB sensor, and any biases computed during the calibration process.

(a) Instrument Calibration Report – The system manufacturer shall provide a factory calibration report describing unique lab calibrations including radiometric and geometric calibrations proving the provided system meets performance specifications.

(b) Flight Calibration Report – Data provider shall provide a calibration report describing the correction of sensor-to-GPS antenna lever arm offsets and system mounting corrections to roll, pitch, and yaw.

(c) Topographic Ranging Bias – Data provider shall provide a topographic ranging bias report for any post-lab calibration ranging bias values calculated.

(d) Bathymetric Depth Bias- Bathymetric depth accuracy from ALB systems are subject to system design, the environment, and post-flight depth bias corrections. For a given system in a particular environment, the data provider shall provide a bathymetric depth bias report for any post-lab calibration depth bias values calculated. Different system designs and depth extraction algorithms manage propagation induced depth biases differently as technology improves to address the environmental response of the transmitted pulse. Along with a report describing the bathymetric depth bias correction, the data provider shall provide comparison results of the corrected ALB data against a trusted bathymetric source. Examples in Figures 7-5 and 7-6 are USACE's CZMIL ALB compared to historic bathymetric data near Fort Lauderdale, FL.

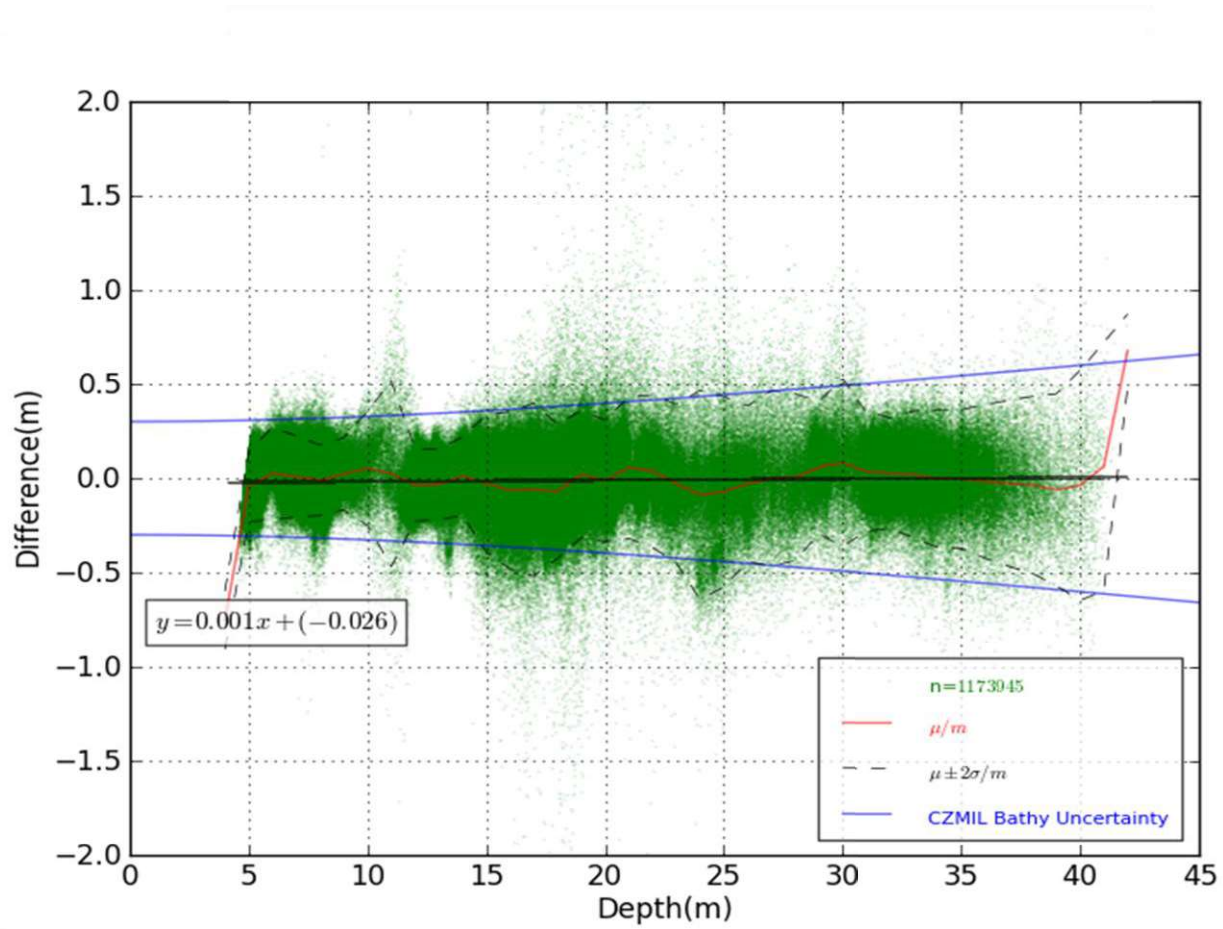

Figure 7-5. CZMIL ALB depth difference when compared to ground truth, displaying no depth biases.

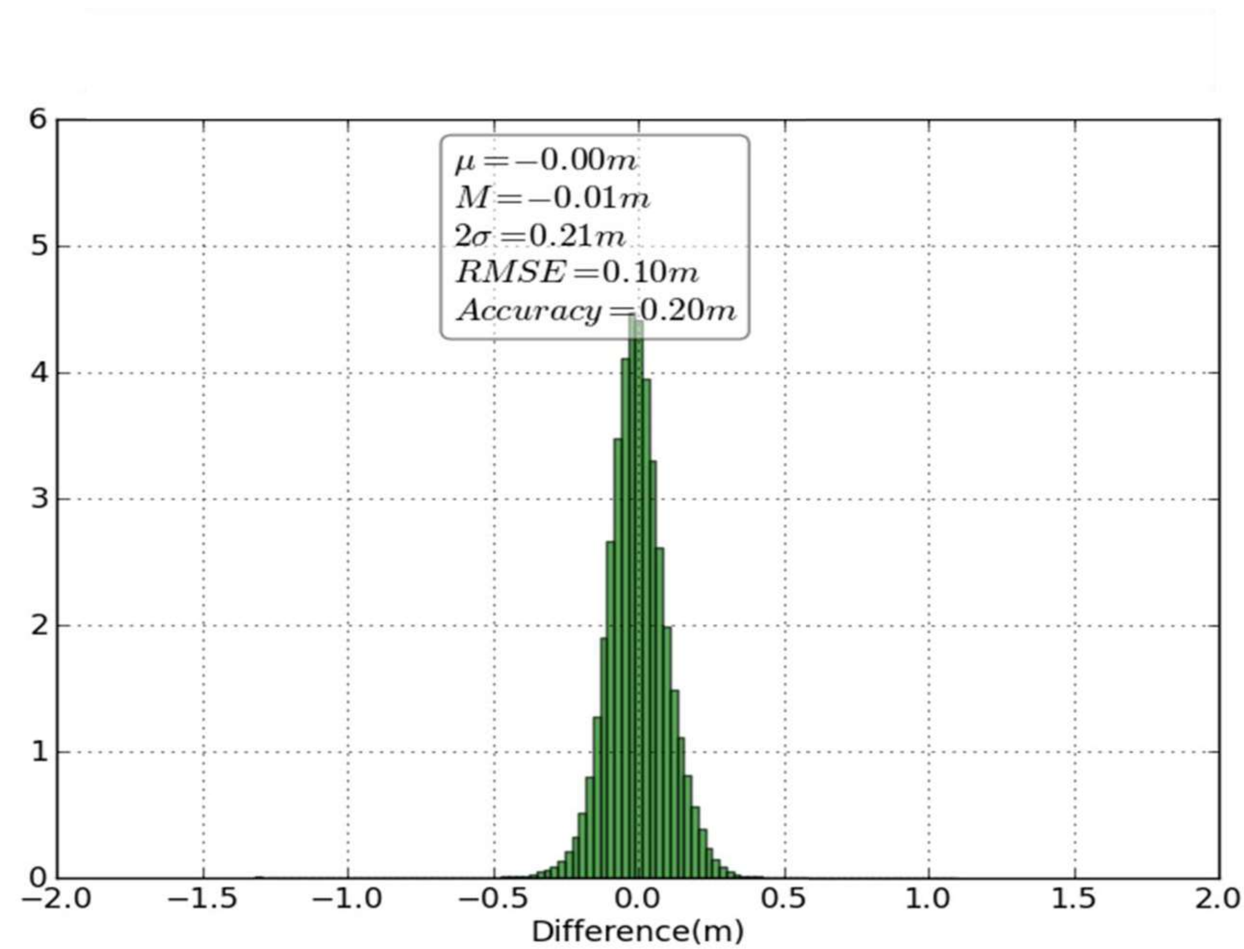

Figure 7-6. CZMIL ALB depth difference when compared to multibeam ground truth distribution and accuracy statistics

(2) <u>Bathymetric Data.</u>

(a) Overlapping lines and datasets shall be compared to each other and to cross lines and the differences calculated.

(b) Each ground truth area (see requirements below) shall be surveyed by a LiDAR cross line. The vertical difference between the LiDAR and ground truth data shall be calculated.

(c) Where possible, ALB data should be compared to other existing LiDAR and sonar datasets. The comparison should show little change over hardbottom, and beyond the depth of closure. JALBTCX data holdings include data for most of the coast of the US and can be contacted directly for a copy of the data. NOAA's Digital Coast and National Geophysical Data Center are both good sources for these pre-existing datasets from both USACE and other Federal agencies' ALB and sonar data.

(d) All systematic errors shall be identified and eliminated and remaining errors should have a normal distribution with a standard deviation < 15 cm.

(3) Topographic Data.

Q24 (a) Overlapping lines and datasets will be compared to each other and the differences computed.

(b) Elevations shall also be verified through comparison with ground truth data as required by ASPRS 2014, with an accuracy specification of 10 cm RMSE in the vertical.

(4) RGB Imagery Data. A comparison of known positions of at least 4 well distributed check points per data tile shall be performed. The 4 positions may be points surveyed on the ground or derived from the LiDAR data. The center of the RGB imagery pixels compared must be located within 3m (RMSEr) relative to the location of the comparison point.

(5) Hyperspectral Imagery Data.

(a) A comparison of known positions of at least 4 well distributed check points per data tile shall be performed. The 4 positions may be points surveyed on the ground or derived from the LiDAR data. The center of the hyperspectral imagery pixels compared must be located within 3m (RMSEr) relative to the location of the comparison point.

(b) Spectrometer observations over pseudo-invariant features shall be compared to the spectral results in the atmospherically corrected hyperspectral imagery.

7-6. Sample Scope of Work and Cost Estimate. A sample scope of work and cost estimate for a regional ALB surveying project are included as Appendix I. The project, while large, is a fairly moderate environment for ALB surveys in that the ALB sensor is expected to produce data in most areas with few re-attempts. Data processing is expected to be straightforward with very little manual editing required. The quantities in the cost estimate reflect these assumptions

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