CHAPTER 7
Airborne Bathymetric LiDAR

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.

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.

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

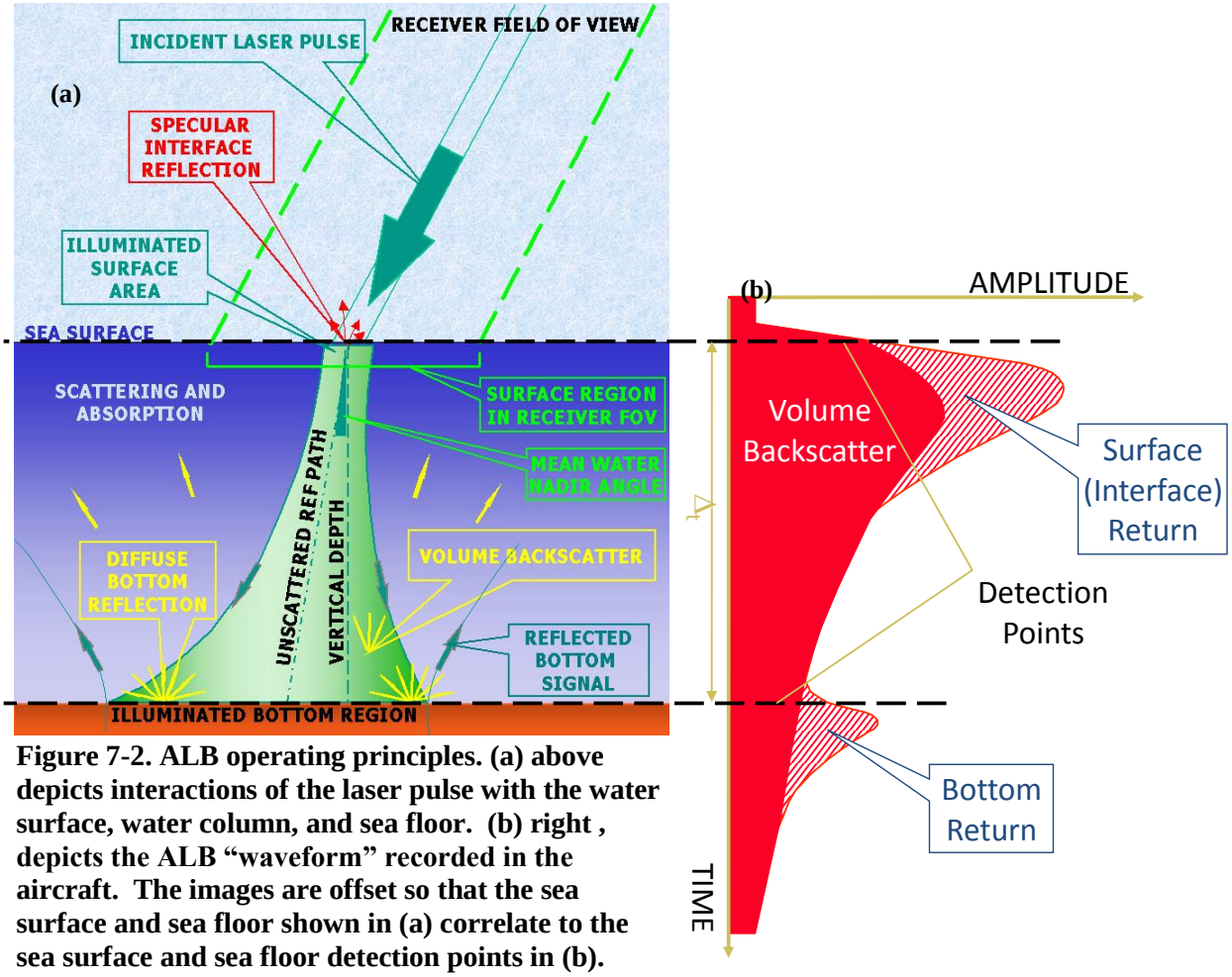


Figure 7-2. ALB operating principles. (a) above depicts interactions of the laser pulse with the water surface, water column, and sea floor. (b) right , depicts the ALB "waveform" recorded in the aircraft. The images are offset so that the sea surface and sea floor shown in (a) correlate to the sea surface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

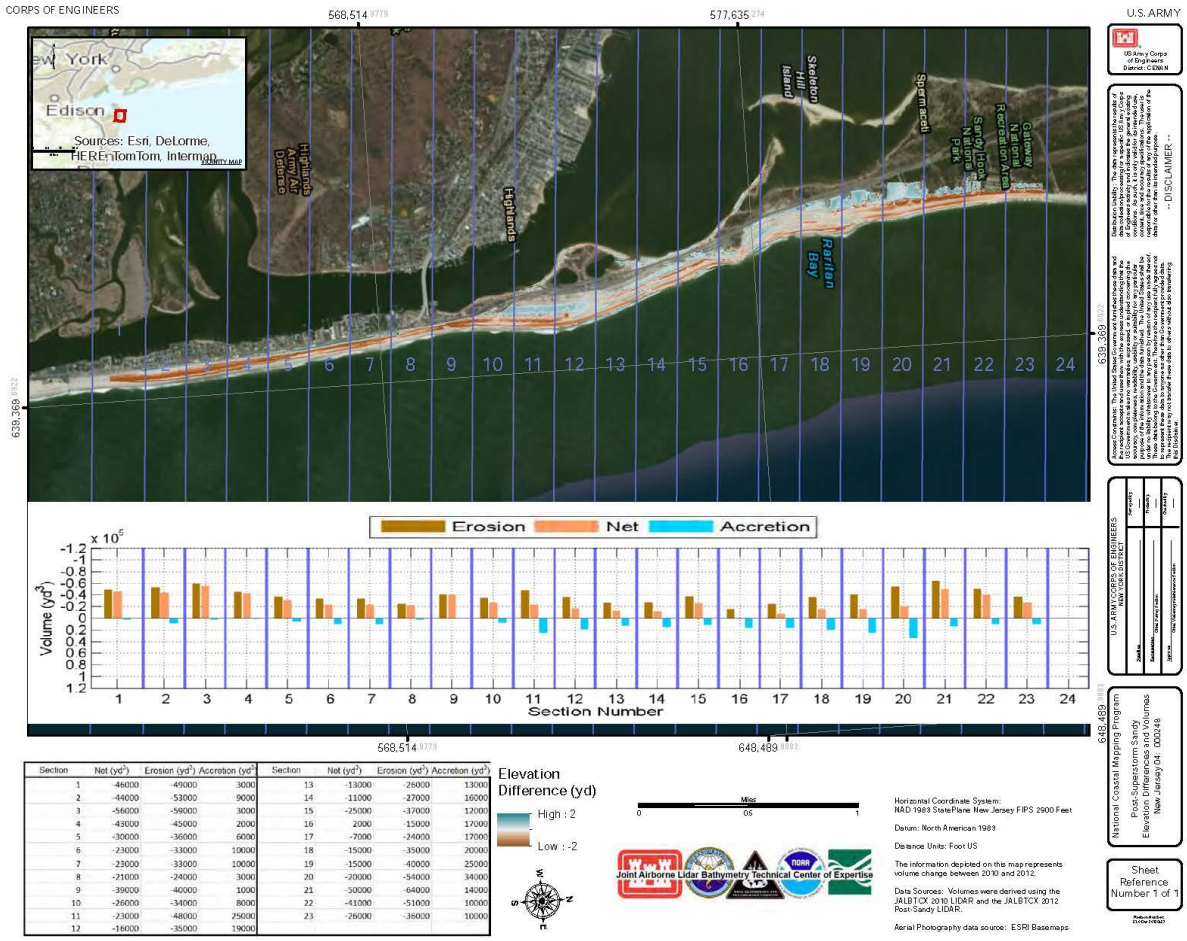
emerged from the topographic LiDAR community. These are generally referred to as "topo-bathy" sensors in that they are primarily topographic LiDAR sensors and have a limited bathymetric capability since they operate at blue-green wavelengths.

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 (yd³)	Erosion (yd³)	Accretion (yd³)	Section	Net (yd³)	Erosion (yd³)	Accretion (yd³)
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	-30000	-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.

c. <u>Define the survey area and intent</u>. 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.

(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.

(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.

(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 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 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

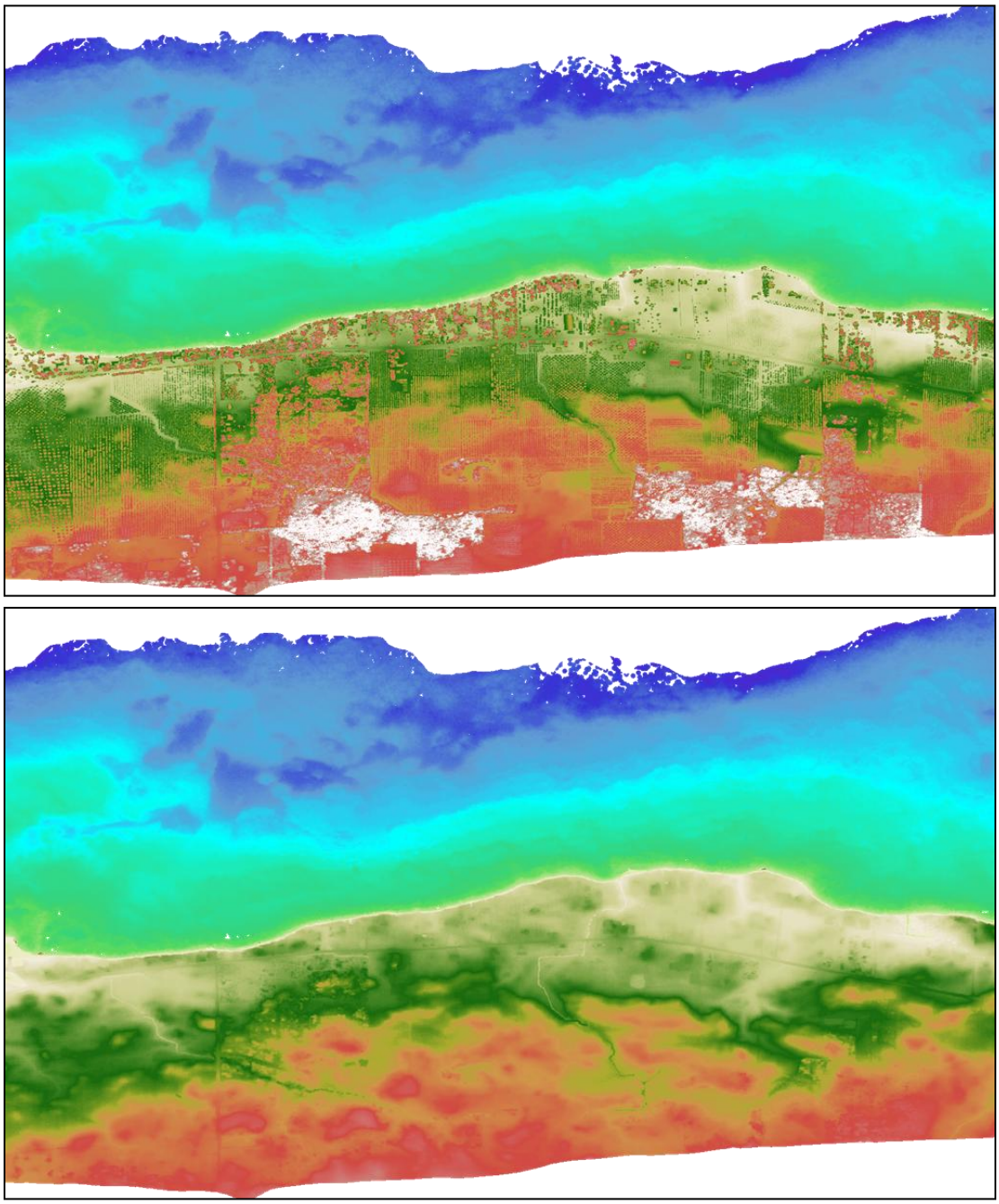


Figure 7-4. Example digital elevation models from the shoreline of Lake Ontario. In both the top and bottom panels, land is at the bottom of the image and water is at the top. The top panel is a DSM that include trees and building in the elevation model. The bottom panel is a DEM, where those and other 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.

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.

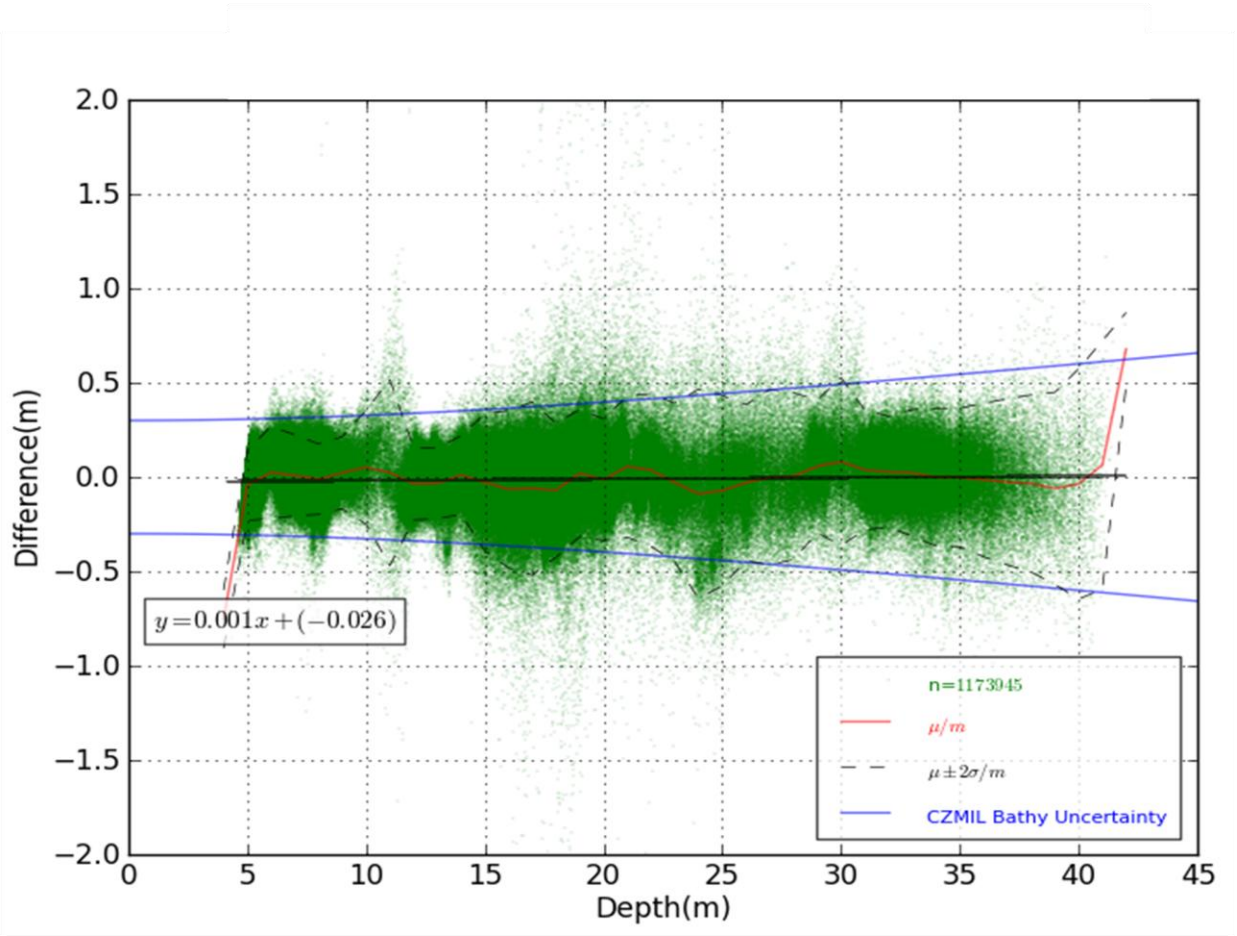


Figure 7-5. CZMIL ALB depth difference when compared to ground truth, displaying no depth biases.

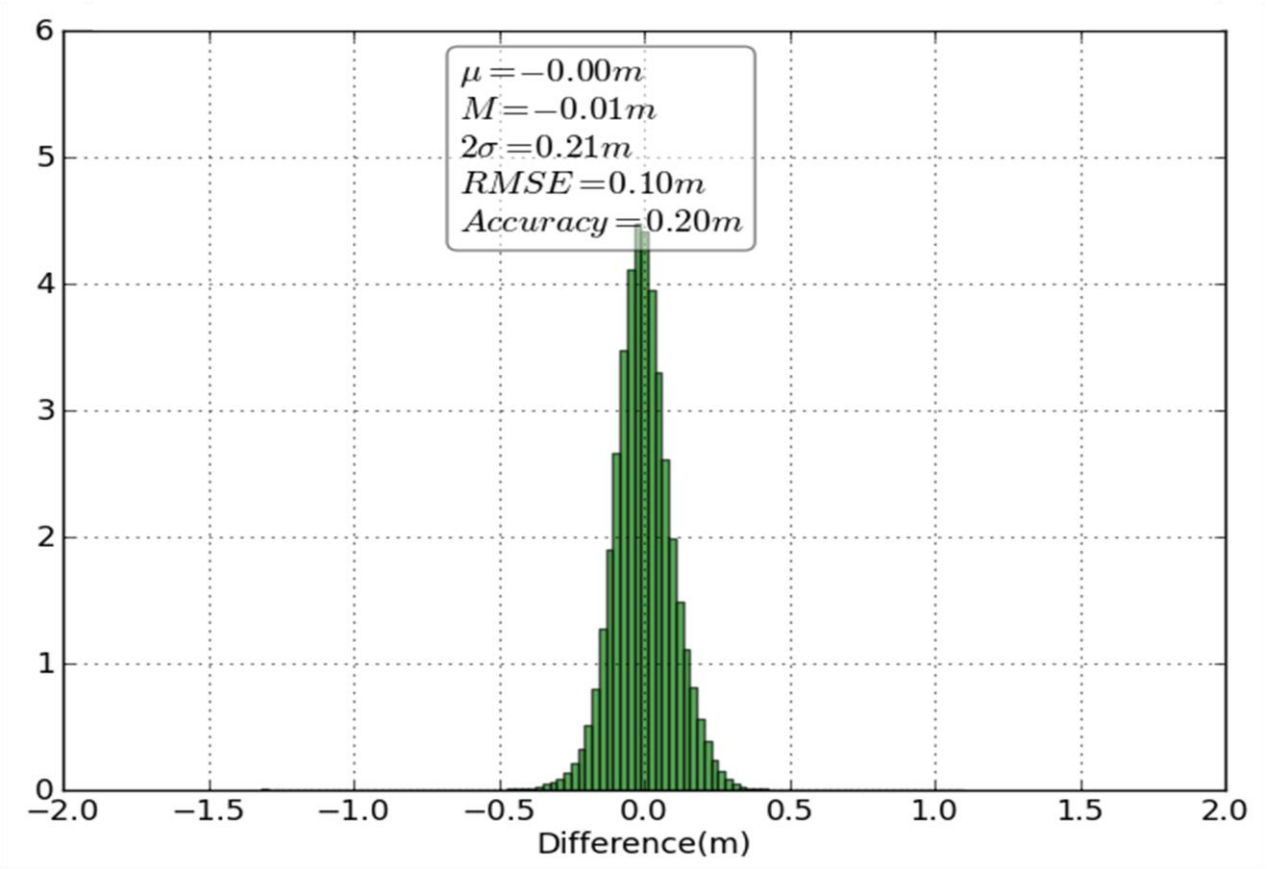


Figure 7-6. CZMIL ALB depth difference when compared to multibeam ground truth distribution and accuracy statistics

(2) Bathymetric Data.

(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.

(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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