		Lidar Vendor	QA/QC Vendor
Phase I	**PRE-FLIGHT PLANNING**		
	Kick-Off Meeting		
	Tasks	*Develop flight operations plan*	
		System calibration and geodetic control validation	
	Deliverables	**Schedule**	**Review and comment**
		Flight plan	
		Sensor calibration report(s)	
Phase II	**DATA ACQUISITION**		
	Tasks	*Perform flight setup and geodetic control process*	*Collect QA/QC checkpoint survey*
		Fly project area to collect data	
		Verify data after each flight mission	
		Collect checkpoint survey	
	Deliverables	**Flight trajectories and GPS report**	**Review and comment**
		Checkpoint table and survey report	
Phase III	**DATA PROCESSING**		
	Tasks	*Boresight/calibration*	
		Point classification	
		Intensity image production	
		Generate hydro-flattening breaklines	
	Deliverables	**PILOT**	**Review Pilot and comment**
		All-return point cloud	**Review data deliverables and comment**
		Hydro-flattening breaklines	
		Intensity images	
		Re-submit Phase III deliverables as necessary	**Approve or reject deliverables**
Phase IV	**FINAL PRODUCT DEVELOPMENT**		
	Tasks	*Create bare-earth DEM*	
		Generate metadata	
	Deliverables	**DEM Raster**	**Review and comment**
		Metadata	
		Re-submit Phase IV deliverables as necessary	**Approve or reject deliverables**
			Deliver whole QA/QC checkpoint table to TWDB
			Submit final QA/QC report
	Project Closeout Meeting		

1. Phases I & II: Pre-Flight Planning and Data Acquisition

1.1 Project Requirements

Nominal pulse spacing (NPS)	**NPS ≤ 0.500 m**, or point density **≥ 4 points per m²** for first-return data.
Uniformity*	Spatial distribution of points must be uniform and free from clustering. 90% of cells in a 1-meter grid will contain at least one first-return point. See Data voids for exclusions.
Buffer	**300 meter buffer** surrounding the AOI is required for flight planning and acquisition, with no buffer needed in between tiles. Buffer will not be included in final delivery.
Multiple returns*	Lidar sensor shall be capable of at least three (3) returns per pulse, including first and last returns. Multiple returns from a given pulse shall be stored in sequential order and point families must remain intact.
Return attributes	Each return must include: easting, northing, elevation, intensity, order of return (i.e. first-return, second-return), classification, and Adjusted GPS Time. Easting, northing, and elevation must be recorded to the nearest **0.01 m** and GPS second reported to the nearest microsecond (or better). May include additional attributes. No duplicate entries.
Scan angle	For lidar systems with an oscillating mirror, scan angle should not exceed ±20 degrees from nadir. Total field of view or full scan angle ≤ 40°. Rotating mirror systems are exempt from this requirement.
Swath overlap	Minimum 30% overlap on adjoining swaths.
Data voids*	Data voids are defined as areas > [(4*NPS)²] with no first-return points. Data voids are unacceptable unless caused by water bodies or areas of low near-infrared (NIR) reflectivity (i.e. wet asphalt). No voids between swaths.
Survey conditions	Leaf-off and no significant snow cover or flood conditions, unless approved by TWDB. Must be cloud, smoke, dust and fog-free between the aircraft and ground.

1.2 GPS Procedures and Accuracy

Positional accuracy validation	The absolute and relative accuracy of the data, both horizontal and vertical, and relative to known control, shall be verified prior to classification and subsequent product development. Report accuracies in metadata as compiled to meet X meters vertical accuracy at the 95% confidence level in open terrain according to the [National Standard for Spatial Data Accuracy (NSSDA)](). Refer to Lidar Accuracy Assessment for details on QA/QC accuracy testing.
Acquisition GPS procedures	At least two (2) GPS reference stations in operation during all missions, sampling positions at 1 Hz or higher frequently. Differential GPS baseline lengths shall not exceed 40 km, unless otherwise approved. Differential GPS unit in aircraft shall sample position at 2 Hz or more frequently. Lidar data shall only be acquired when GPS PDOP is ≤ 4 and at least 6 satellites are in view.
Geodetic control	Lidar vendor must supply ground control for acquisition and processing. See Quality Assurance and Quality Control portion of this document for recommended collection guidelines.

AccuracyASPRS Class 10cm	Non-Vegetated	**$RMSE_z$**	**< 10 cm**
		$Accuracy_z$ 95%	< 19.6 cm
	Vegetated	$Accuracy_z$ 95%	< 29.4 cm
	Horizontal	$RMSE_r$	< 25.0 cm
	Relative (swath to swath)**	$RMSD_z$/Max Diff	< 8.0/16.0 cm

*In accordance with USGS Lidar Base Specification Version 1.2

2. Phases III & IV: Data Processing and Product Development

2.1 Fully Classified All-Return Point Cloud

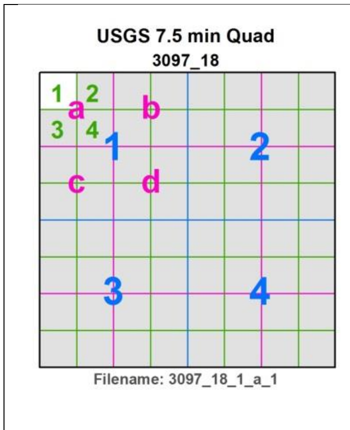
Format	All-return point cloud in fully-compliant LAS version 1.4. All points must be classified according to the ASPRS classification standard for LAS.		
Spatial reference	LAS files will use the Spatial Reference Framework according to project specification and all files shall be projected and defined.		
ASPRS Classifications Required	**Class 1. Unclassified** **Class 2. Bare-earth Ground** **Class 3. Low Vegetation**	**Class 4. Medium Vegetation** **Class 5. High Vegetation** **Class 6. Building** **Class 7. Low Point (noise)**	**Class 9. Water** **Class 10. Ignored ground** **Class 13. Bridges** **Class 14. Culverts**
Withheld points*	Outliers, noise, blunders, geometrically unreliable points near the extreme edge of the swath, and other points deemed unusable are to be identified using the "Withheld" flag. This applies primarily to points which are identified during pre-processing or through automated post-processing routines. Subsequently identified noise points may be assigned to the standard Noise Class (Class 7), regardless of whether the noise is lower or higher relative to the ground.		
Overlap class*	The ASPRS Overlap Class (Class 12) shall **NOT** be used. All points must be classified unless identified as "Withheld".		
Classification accuracy*	**Within any sample 1 km x 1 km area, no more than 1% of non-withheld points in the classes listed above** will possess a demonstrably erroneous classification value. This includes Unclassified points (Class 1) that should be correctly included in a different class as required by this specification. This requirement may be relaxed to accommodate collections in areas where the TWDB agrees classification to be particularly difficult.		
Classification consistency*	Point classification shall be consistent across the entire project. Noticeable variations in the character, texture, or quality of the classification between tiles, swaths, lifts, or other non-natural divisions will be cause for rejection of the entire deliverable.		

2.2 Bare Earth Lidar / Digital Elevation Model Raster

Format	Hydro-enforced 32-bit floating point raster DEM in (TBD at kick-off meeting) format to nearest 0.01 m is preferred, however similar raster formats may be permitted at the discretion of the TWDB.
Spatial reference	DEM files will use the Spatial Reference Framework according to project specification and all files shall be projected and defined.
Spatial resolution	**1-meter DO4Q tiles (See File Naming Convention)**
DEM tile buffer	All final DEM tiles should be delivered with a buffer that extends 50 meters around all four sides of the DEM tile. All final DEM tiles should have 90 degree corners, not rounded. The extents shall be computed by projecting the geographic corners and side midpoints to the required projection, then adding the buffer on each side of the resulting minimum bounding rectangle.
Quality	No seams, stepping, gaps, or quilting should be visible (unless naturally occurring), whether caused by differences in processing quality or character between tiles, swaths, lifts, or other non-natural divisions and will be cause for rejection of the entire DEM deliverable. There shall be no "plateau effect" from rounded or integer elevation values (must be floating point). Also see 'Data voids' under Project Requirements.
Artifacts	Vegetation, bridges, buildings, and other artifacts must be completely removed from Class 2 Bare-earth Ground. Artificial dams in waterways caused by bridges or other adjacent structures are not permitted with the exception of culverts. See 'Culverts' under Hydro-flattening Breaklines for more information. Bare-earth lidar points that are near the breaklines shall

	be classified as Ignored Ground (Class 10) and be excluded from the hydroflattened DEM creation process to prevent surface artifacts from being created between mass points and breakline vertices. The proximity threshold for reclassification as Ignored Ground in general will not exceed the ANPS.
Filtering	There shall be no over-aggressive filtering of the Ground class resulting in gaps or a degradation of DEM quality (e.g. hilltops shaved flat or data voids). There shall also be no under-aggressive filtering of the Ground class resulting in a degradation of DEM quality (e.g. portions of buildings or vegetation included in Ground or overly noisy surface).
Sinks	Depression sinks, natural or man-made (not erroneous), are **not** to be filled (as in hydro-conditioning).
Breaklines	Hydrologic breaklines shall be used to define stream/river channels and water bodies allowing for unimpeded water flow. See Hydro-flattening Breaklines below for more information.
No data	Data voids outside the project boundary shall be coded as NODATA (-32767), as well as acceptable internal voids.
2.3 Hydro-flattening Breaklines	
Format	All breaklines developed for use in hydro-flattening shall be delivered as a non-tiled Esri feature class for the entire AOI in polygon and/or polyline shapefile or geodatabase format. Waterbodies (ponds, lakes, and reservoirs), wide streams and rivers ("double-line"), and other non-tidal waterbodies are to be hydro-flattened within the DEM, resulting in a flat and level bank-to-bank gradient. The entire water surface edge must be at or below the immediately surrounding terrain.
Spatial reference	Breakline feature class will use the Spatial Reference Framework according to project specification and shall be projected and defined.
Stream resolution	Hydro-flattening shall be applied to all streams that are nominally wider than **15.25 meters**, and to all non-tidal boundary waters bordering the project area regardless of size. Stream features should be made continuous even when a segment narrows below this threshold for a distance of at least 1600 meters to maintain cartographic integrity. Flattened rivers and streams shall present a gradient downhill water surface, in accordance with the immediately surrounding terrain. In cases of drought, flood or rapidly moving water demonstrating conditions where the water surface is notably not level bank to bank, the water surface will be represented as it exists during acquisition while maintaining an aesthetic cartographic appearance.
Waterbody resolution*	Hydro-flattening shall be applied to all water impoundments, natural or man-made, that are nominally larger than **1 hectare** in area (equivalent to 10,000 m^2 or roughly equivalent to a round pond ~100 meter in diameter). Long impoundments such as reservoirs, inlets, and fjords, whose water surface elevations drop when moving downstream, are required to be treated as rivers.
Non-tidal boundary waters*	Represented only as an edge or edges within the project area; collection does not include the opposing shore. Water surface is to be flat and level, as appropriate for the type of water body (level for lakes; gradient for rivers). The entire water surface edge must be at or below the immediately surrounding terrain.
Tidal waters*	Tidal water bodies are defined as water bodies such as oceans, seas, gulfs, bays, inlets, salt marshes, large lakes, and the like. This includes any water body that is affected by tidal variations. Tidal variations over the course of a collection or between different collections will result in lateral and vertical discontinuities along shorelines. This is considered normal and these anomalies should be retained. The final DEM is required to represent as much ground as the collected data permits. Water surface is to be flat and level, to the degree allowed by the irregularities noted above. Scientific research projects in coastal areas often have specific

	requirements with regard to how tidal land-water boundaries are to be handled. For such projects, the requirements of the research will take precedence.
Islands*	Permanent islands 5,000 m^2 or larger shall be delineated within all water bodies.
Culverts	Stream channels should break at road crossings (culvert locations). These road fills in Class 14 Culverts should not be removed from the DEM. However, streams and rivers should not break at elevated bridges. Bridges should be removed from the DEM (see 'Artifacts' under Bare Earth Lidar/DEM Raster). When the identification of a feature such as a bridge or culvert cannot be made reliably, the feature should be regarded as a culvert.
2.4 Intensity Images	
Format	Raster image of first-return intensity values in GeoTiff.
Spatial reference	Intensity images will use the Spatial Reference Framework according to project specification and all files shall be projected and defined.
Spatial resolution	**≤ 1-meter DO4Q tiles**
Image tile buffer	All final image tiles should have a buffer that extends 50 meters around all four sides of the image tile. All final image tiles should have 90 degree corners, not rounded. The extents shall be computed by projecting the geographic corners and side midpoints to the required projection, then adding the buffer on each side of the resulting minimum bounding rectangle.
Radiometric resolution	Unsigned 8-bit, 16-bit or 32-bit (highest available). Intensity images should typically contain original digital number (DN) values ranging from 0 - 100 or greater for ≥ 80% of areas with diverse land cover conditions.
Histogram	Histogram should be very close to normally distributed with minimal or no clipping.
Consistency	Images should be consistent in contrast and tone across project AOI. There should be no striping, tiling, or banding across project AOI.
2.5 Metadata	
Format	Tile-level metadata consisting of separate XML files paired with each data tile as well as project-level metadata for non-tiled data in XML format.
FGDC Standard	All metadata shall be consistent with the Federal Geographic Data Committee's Content Standards for Digital Geospatial Metadata.
Methodology	Metadata will include processing steps and software used. If requested, sample metadata will be provided by TWDB.
2.6 Spatial Reference Framework	
Vertical Datum	NAVD88 with most recent NGS-approved geoid to convert from ellipsoidal to orthometric heights
Horizontal Datum	NAD83 (2011)
Projection	UTM – Project AOIs covering more than one UTM zone shall be split along the UTM boundary with one (1) row of overlapping tiles on each side duplicated and projected into both zones.
Vertical Units	Meters (Orthometric, NAVD88)
Horizontal Units	Meters (UTM)
2.7 File Naming Convention	

	Applies to the following: **All-return point cloud in LAS** **Bare-earth DEM** **Intensity images** **Tile-level metadata** Structure for data listed above shall conform to: 1/64th USGS 7.5-minute quadrangle Quarter-quarter-quarter quadrangle **(DOQQQQ, or DO4Q)**

3. Deliverables

3.1 Phase I Deliverables

Schedule	**Project timeline (schedule) with projected milestones should also include due dates for BOTH Phase III and Phase IV, to be separated by at least six weeks for QA/QC.** Schedule should be provided to TWDB in a PDF, .docx, or .xlsx format.
Flight plan	Flight plan for each AOI shall include: aircraft flight lines and GPS base stations in use during acquisition delivered in Esri feature class, shapefile, or kmz/kml format.
Sensor Calibration Report	Most recent calibration report for all lidar sensors used for collection.

3.2 Phase II Deliverables

Flight trajectories	Smoothed Best Estimate of Trajectory (SBET) files with recorded aircraft position (easting, northing, elevation) and attitude (heading, pitch, roll) and Adjusted GPS time recorded at regular intervals of 1 second or less and delivered in Esri feature class or shapefile format. May include additional attributes.
Flight report	Flight report should include at a minimum the following mission parameters: sensor make and model, nominal ground sampling distance, scan angle, average groundspeed, laser pulse rate, scan rate, and average flying altitude. Network parameters with base station IDs and location should be included as well as flight PDOP.
Control table	Any checkpoints collected by the lidar vendor for internal quality control shall be provided to TWDB in an electronic table (csv, ASCII, xls(x), shp) including UTM coordinates (X,Y,Z) to three (3) decimal places, point ID and land cover type, at a minimum.
Control survey report	Along with control table, lidar vendor shall submit associated survey report including at a minimum selected geodetic control network and spatial parameters (i.e. coordinate system, geoid model).

3.3 Phase III Deliverables

Pilot Data	The lidar vendor (in consultation with TWDB and project partners) will select a minimum of four (4) contiguous tiles within the project AOI which shall serve as a Pilot area. The Pilot will be delivered to TWDB and the QA/QC review consultant and shall include all-return point cloud, DEM and intensity image products delivered in final product form to meet or exceed the specifications established in this document. It is recommended that processing of other data in the AOI be suspended until the Pilot data have been approved by TWDB.
All-return point cloud **Hydro-flattening breaklines** **Intensity images**	To be received by QA/QC review consultant on or before Phase III Deliverables due date. See section above titled ***Phases III & IV: Data Processing and Product Development*** for details. Final products must pass QA/QC review before acceptance.

3.4 Phase IV Deliverables

DEM raster **Metadata**	To be received by QA/QC review consultant on or before Phase IV Deliverables due date. See section above titled ***Phases III & IV: Data Processing and Product Development*** for details. Final products must pass QA/QC review before acceptance.

3.5 Intellectual Property Rights

The contracting agency shall have unrestricted rights to all delivered reports and data. The contracting agency expects to place reports and data in the public domain.

4. Quality Assurance and Quality Control

4.1 Checkpoint Acquisition

Checkpoint planning, acquisition and testing methodologies must follow the 2014 ASPRS Accuracy Standards for Digital Geospatial Data.

Number of checkpoints	Number of checkpoints for vertical accuracy testing of lidar should follow ASPRS recommendations in Table C.1 of the 2014 ASPRS Accuracy Standards for Digital Geospatial Data unless otherwise specified by TWDB.
Checkpoint distribution	Checkpoint distribution shall be recommended by the QA/QC contractor in consultation with TWDB. Checkpoints may be located in either vegetated or non-vegetated areas depending on land cover characteristics of the AOI. Ideally checkpoints will be located in accessible public lands or right-of-way.
Elevation	The most recent NGS-approved geoid shall be used to convert GPS ellipsoid heights (NAVD88) into orthometric heights for each checkpoint.
Checkpoint table	**Deliverable 1:** The surveyor will provide TWDB and the QA/QC team with all checkpoints collected including (at a minimum) UTM coordinates (X,Y,Z) to three (3) decimal places, point ID and land cover type. Point data must be in electronic format. Acceptable formats include: ASCII, .csv, .txt, .shp, .xls(x), .mdb
Checkpoint survey report	**Deliverable 2:** Along with checkpoint table, QA/QC contractor shall submit associated survey report including at a minimum selected GPS network (i.e. RTK) and spatial parameters (i.e. coordinate system, geoid model) as well as reference site photos. Acceptable formats include: .doc(x), .pdf,

4.2 Lidar Accuracy Assessment

Non-vegetated vertical accuracy (NVA)	The QA/QC contractor will follow the 2014 ASPRS Accuracy Standards for Digital Geospatial Data to compute the vertical $RMSE_z$ and $Accuracy_z$ at a 95% confidence interval ($RMSE_z$*1.96) in centimeters for **checkpoints located in non-vegetated open terrain**.
Vegetated vertical accuracy (VVA)	The 95^{th} percentile method shall be used to determine vertical accuracy for **checkpoints located in vegetated terrain**, regardless of vegetation type. The least accurate 5% of checkpoints shall be discarded and the $RMSE_z$ and $Accuracy_z$ will then be calculated and reported.
Lidar accuracy assessment report	**Deliverable 3:** If the 95^{th} percentile $RMSE_z$ and $Accuracy_z$ calculation passes the accuracy criteria listed for the lidar vendor (under GPS Procedures and Accuracy), the QA/QC team will prepare a Lidar Accuracy Assessment Report declaring the data have passed. The official report will include statistics, compared with the relevant accuracy standard.

4.3 Project Review and Final Report

Phase I: Pre-Flight Planning	Review Phase I parameters and deliverables from lidar vendor including: project parameters; timeline; flight plan; sensor calibration report and provide comments/feedback to vendor and TWDB. See requirements listed above for details.
Phase II: Data Acquisition	QA/QC vendor will be available to lidar vendor or TWDB for input or advice regarding data acquisition.
Phase III: Pilot	Review pilot area submitted by lidar vendor to ensure all requirements in this specification are met. Provide comments/feedback to lidar vendor and TWDB. An accuracy check and formal reporting are not required.

Phase III: Data Processing	Review Phase III deliverables (LAS, intensity images, hydro-flattening breaklines), check accuracy and provide comments/feedback to lidar vendor and TWDB. If the data are rejected for any reason, notification to TWDB and the lidar vendor should occur as soon as possible for corrective measures. Phase IV shall not commence until Phase III data meet specification.
Phase IV: Final Product Development	Review Phase IV deliverables (DEM raster, metadata) and provide comments/feedback to lidar vendor and TWDB. Approve or reject deliverables based on compliance with project specification in consultation with TWDB.
Final QA/QC report	**Deliverable 4:** Document all workflow processes as well as quantitative and qualitative findings in a detailed report which will also include Checkpoint Survey Report and Lidar Accuracy Assessment Report. Screenshots and other graphics are encouraged. Acceptable formats include .doc(x), .pdf

References

American Society for Photogrammetry & Remote Sensing. ASPRS Guidelines Vertical Accuracy Reporting for Lidar Data. 24 May 2004. http://www.asprs.org/a/society/committees/lidar/Downloads/Vertical_Accuracy_Reporting_for_Lidar_Data.pdf

American Society for Photogrammetry & Remote Sensing. LAS Specification Version 1.4-R6. 10 June 2012. http://www.asprs.org/a/society/committees/standards/LAS_1_4_r12.pdf

Federal Geographic Data Committee. Content Standard for Digital Geospatial Metadata (FGDC-STD-001-1998). 1998. http://www.fgdc.gov/metadata/csdgm

Federal Geographic Data Committee. Geospatial Positioning Accuracy Standards Part 3: National Standard for Spatial Data Accuracy. 1998. http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part3/chapter3

GeoTiff Format Specification, GeoTiff Revision 1.0 (Version 1.8.2). 28 December 2000. http://www.remotesensing.org/geotiff/spec/geotiffhome.html

Heidemann, Hans Karl. U.S. Geological Survey Lidar Base Specification Version 1.0. 17 August 2012. http://pubs.usgs.gov/tm/11b4/

Maune, David F. Digital Elevation Model Technologies and Applications: The DEM Users Manual, 2nd Edition. 2007.

Maune, David F. FEMA's Mapping and Surveying Guidelines and Specifications. 2003. http://w.psadewberry.com/Libraries/Documents/FEMAs_Mapping_and_Surveying_Guidelines_and_Specifications_ASPRSFall2003.pdf

National Digital Elevation Program. Guidelines for Digital Elevations Data (Version 1.0). 10 May 2004. http://www.ndep.gov/NDEP_Elevation_Guidelines_Ver1_10May2004.pdf

The National Geodetic Survey. The NGS Geoid Page. 11 September 2012. http://www.ngs.noaa.gov/GEOID/

Ritter, Niles and Mike Ruth. GeoTiff Format Specification GeoTiff Revision 1.0. 28 December 2000. http://www.remotesensing.org/geotiff/spec/geotiffhome.html

U.S. Geological Survey. Multi-Resolution Land Characteristics Consortium: National Land Cover Database. 2006. http://www.mrlc.gov/