3DEP Lidar Base Specification 2020 rev. A

Introduction

This document is a copy of the 3DEP Lidar Base Specification 2020 rev. A as found on the USGS National Geospatial Program Standards and Specifications website. For the latest version of the specification, please visit the site: https://www.usgs.gov/3DEP/lidarspec

Revision History

Version 2020 rev. A

1. Changed the version naming for clarity and improved version control.
2. Updated LAS references from LAS specification version 1.4-R13 to LAS 1.4-R15 (ASPRS, 2011).
3. Updated latest geoid from GEOID2012b to GEOID18.
4. Added requirement for photographs of checkpoints.
5. Expanded vertical accuracy requirements to include ground-classified points.
6. Revised use of the withheld flag.
7. Clarified Class 0 and Withheld requirements.
8. Revised unrestricted rights and delivery clause.
9. Revised swath polygon requirements.
10. Added requirement for Swath Separation Images in Metadata.

Version 2.1

1. Eliminated Buffered Project Area (BPA) language.
2. Updated point classification requirements. The section on Point Classification is replaced with:
   - The minimum, required classification scheme for lidar data is found in table 5.
   - All points that fall within the minimum classification scheme (table 5) and not flagged as withheld shall be properly classified.
   - Additional classes may be used on specific projects.
   - Accuracy of point classification into classes beyond the minimum scheme (table 5) will not be assessed by the USGS, as documented in metadata.
   - Assessing and verifying accuracy of point classification into classes beyond the minimum scheme will be the responsibility of the partner requesting the additional classes.
   - No points in the classified LAS deliverable may remain assigned to Class 0.
   - Points classified as water will only be checked when associated with a breakline.
   - If it is necessary to identify overage points in overlap areas, the overage points shall be identified using the overlap bit flag as defined in LAS Specification Version 1.4-R13 (ASPRS, 2011).
   - No classification code may be used to identify points as overage points.
3. Changed DEM delivery format from preferring ERDAS Imagine (.img) to requiring GeoTIFF with the following requirements:
   - 32-bit floating-point GeoTIFF raster format.
   - The NODATA value of '-999999' shall be defined in GDAL_NODATA tag #42113.
   - GDAL version 2.4.0, or as otherwise agreed to in advance and specified in the Task Order, shall be used to populate GeoTIFF keys and tags.

- Additional requirements for GeoTIFF tiling, compression, and internal overviews may be referenced in Task Orders.

4. Added a requirement for the use of '-999999' as a single, consistent NODATA value:
    - Void areas coded using a NODATA value of '-999999' and shall be defined in GDAL_NODATA tag #42113.

Version 2.0

1. Changed review and approval process. The National Geospatial Program's Elevation Specification Review Board (ESRB) and the 3D Elevation Program Working Group (3DEP WG) must approve all changes.
2. Changed the delivery method--the Lidar Base Specification will be published online through the Specifications Explorer (Spec-X) database and web application as well as on the 3DEP Standards and Specifications website.
3. Added requirements for bridge treatment:
    - All instructions and requirements regarding the use of breaklines also applies to non-hydrographic terrain generation below bridges.
    - Any breaklines used to enforce a logical terrain surface below a bridge shall be considered a required deliverable.
    - The bare-earth surface below the bridge shall be a continuous, logical interpolation of the apparent terrain lateral to the bridge deck.
    - Where abutments are clearly visible, the bare-earth interpolation shall begin at the junction of the bridge deck and approach structure. Where this junction is not clear, the contractor shall use their best judgement to delineate the separation of below-bridge terrain from elevated bridge surface.
    - Streams, rivers, and water bodies meeting the criteria for hydro-flattening shall be monotonically continuous where bridge decks have been removed.
    - Bridges, as defined in the glossary, shall be removed from the bare-earth surface.

Version 1.3

1. The requirement for delivery of raw, unclassified swath data has been removed.
2. The requirement for XML metadata files for the overall project and for individual lifts has been removed.
3. A requirement to use Geoid12b to convert from ellipsoid heights to orthometric heights has superseded Geoid12a.
4. A requirement that specific coordinate reference system (CRS) information for all projects be agreed upon prior to collection has been added.
5. A requirement for vertical CRS information has been added.
6. A requirement to include the geoid model as part of the vertical CRS name has been added.
7. A requirement to represent horizontal and vertical CRS information as a compound CRS has been added.
8. A requirement that delivered raster elevation files must contain complete and correct georeference information for horizontal and vertical systems, including geoid model used, has been added.
9. A requirement for horizontal accuracy reporting has been added.
10. A requirement for delivery of ancillary products used to support processing of the lidar dataset has been added.
11. A requirement for an attributed polygon feature class representing individual swath boundaries has been added.
12. A clarification on the well-known text (WKT) representation of CRS has been added.

13. A clarification on intensity normalization has been added.
14. A clarification on handling of multiple CRS records in LAS files has been added.
15. A clarification on file source identifier (ID) for tiled LAS files has been added.
16. A clarification of the difference between overlap and overage has been added.
17. A clarification on the identification of overage (overlap) points has been added.
18. A clarification on requirements for the use of overlap and withheld point flags has been added.
19. A clarification on how model key points shall be identified using the LAS key point bit flag has been added.
20. The recommended process for assessing intraswath relative accuracy (repeatability, precision) has been refined to normalize for the natural slope.
21. The recommended process for assessing interswath relative accuracy has been limited to areas with less than (<) 10-degree slope.
22. The maximum limits for interswath differences have been removed.
23. A prohibition on duplication of points within a project has been added.
24. The classification code for “Ignored Ground” (typically used for breakline proximity) has been changed from 10 to 20 to correct the conflict with the ASPRS defined code for “Rail.”
25. A classification code for “Snow” (21) has been added.
26. A classification code for “Temporal Exclusion” (22) has been added.
27. Definitions of swath types have been added to the “Glossary” section.
28. Guidelines for breakline collection, compliant with a newly added EleHydro data dictionary have been added.
29. All references to the National Elevation Dataset (NED) have been changed to “the standard national DEM available through The National Map.” The names “National Elevation Dataset” and “NED” are no longer used for data collected and processed for The National Map or 3DEP.

Version 1.2

1. For clarification, the publication was modified to omit versioning from the main title. No changes were made to the content of the specification.

Version 1.1

1. For clarification, numerous sections of the specification were editorially revised and there was minor reorganization of the document.
2. Concurrently with USGS development of the LBS version 1.1, the American Society of Photogrammetry and Remote Sensing (ASPRS) developed the “Positional Accuracy Standards for Digital Geospatial Data” (American Society of Photogrammetry and Remote Sensing [ASPRS], 2014). Glossary definitions in the LBS were updated to align with those in ASPRS (2014) and other industry publications, and several new definitions were added. Notable among these are the following:
    - aggregate nominal pulse density (and spacing)
    - bridge and culvert
    - vegetated vertical accuracy (VVA) and nonvegetated vertical accuracy (NVA)
    - percentile
3. With regard to elevation data, the new standards rede- fine how elevation accuracy is described and reported, and although any accuracy could be its own accuracy class, a number of specific common classes are explicitly defined. These new ASPRS standard classes are slightly different from those defined by the previous ASPRS standards. Earlier accuracy classes were the basis for the NEEA QL definitions; therefore, the QL accuracy definitions

were adjusted to match the new ASPRS classes and to eliminate confusion about accuracy requirements as 3DEP moves forward. Another QL, QL0, was added as a placeholder for the higher-quality data anticipated with future advances in lidar technology. The requirements stated for QL0 are somewhat arbitrary and are subject to change in future revisions of this specification. The changes relevant to lidar data QLs in this revision of the specification were as follows:

- QL0 was added with accuracy of 5.0-centimeter (cm) vertical linear root mean square error in the *z* direction ($RMSE_z$) and density of at least 8 pulses per square meter (pls/m^2). This aligns with the ASPRS 5-cm vertical accuracy class.
- QL1 accuracy was changed from 9.25-cm $RMSE_z$ to 10.0-cm $RMSE_z$. This does not correspond directly to any ASPRS accuracy class; it is a hybrid of QL2 accuracy and QL0 pulse density.
- QL2 accuracy was changed from 9.25-cm $RMSE_z$ to 10.0-cm $RMSE_z$. This aligns with the ASPRS 10-cm vertical accuracy class. QL2 pulse density remains unchanged at 2 pls/m^2.
- QL3 accuracy was changed from 18.5-cm $RMSE_z$ to 20.0-RMSE and density was changed from 0.7 pls/m^2 to 0.5 pls/m^2. This aligns with the ASPRS 20-cm vertical accuracy class.

4. In addition, to align with the new ASPRS accuracy standards, accuracy reporting requirements were defined as based on NVA and VVA. These two classes replaced the previously used fundamental, supplemental, and consolidated vertical accuracy (FVA, SVA, and CVA, respectively) classes.
5. The new ASPRS standards include recommendations tying the quantity of vertical accuracy check points required for a project to the areal extent of the project. This revision of the specification required adherence to these recommendations.
6. QL2 was established as the minimum required QL for new USGS–NGP lidar data collections.
7. Relative accuracy requirements for lidar data, within swath (intraswath) and between overlapping swaths (interswath), were refined and established for each QL. A more detailed methodology for assessing and reporting these metrics was provided.
8. Lidar data delivery is now required in LAS specification version 1.4–R13 (ASPRS, 2011), point data record for- mat (PDRF) 6, 7, 8, 9, or 10. Proper use of the overlap and withheld bit flags is required.
9. The block of lidar specific metadata tags recommended in the previous version of this specification was modified to reflect the other updates to the specification. The inclusion of this block is now required in all lidar data eXtensible Markup Language (XML) metadata files.
10. The 2-gigabyte (GB) limit on swath file size was removed, although the method for splitting large swath files remains in the specification for use in situations where a data producer needs to produce smaller files.
11. The test area for assessing classification accuracy was corrected from 1 kilometer square to 1 square kilometer.
12. Two additional point classification type requirements were defined:
    - Class 17, Bridges
    - Class 18, High Noise
13. Anticipating that projects will more frequently use multiple coverage collection (for example, overlap greater than 50 percent) to achieve the higher pulse density required, terminology and requirements for this data organization were added.
14. Requirements for datum and coordinate reference systems were refined and clarified.

15. Development and delivery of breaklines were required for all hydro-flattened waterbodies, regardless of the methodology used by the data producer for hydro- flattening.
16. Requirements and guidelines for flightline overlap and scan angle limits were removed. Data producers were cautioned that more rigorous attention will be paid to gaps in and the relative accuracy of the point data.

Collection Requirements

Lidar collection parameters are highly dependent on the environment of the project area and numerous additional factors. Although these variations must be accepted, this section defines a number of collection requirements that must be met to achieve the consistent national lidar collection at the heart of 3DEP.

Collection Area

- The Defined Project Area (DPA) shall be the Area of Interest (AOI) plus a 100-meter buffer.
- Data collection is required for the full extent of the DPA.
- All products shall be produced to 3DEP and Task Order requirements up the edge of the DPA.
- All data and products shall be delivered to the customer for the full extent of the DPA.
- All products, including checkpoints, shall be located within or otherwise clipped to DPA extents.

Quality Level

- The minimum acceptable Quality Level (QL) for 3DEP collections is QL2 as defined in this specification. *See* tables 1-6 for detailed QL requirements.

Multiple Discrete Returns

- Deriving and delivering multiple discrete returns are required in all conventional lidar data collection efforts.
- Data collection shall be capable of at least three returns per pulse.
- Full waveform collection is acceptable and is promoted; however, full waveform data are regarded as supplemental information.

Intensity Values

- Intensity values are required for each multiple discrete return.
- The intensity values recorded in the LAS files shall be normalized to 16 bit, as required by the LAS specification version 1.4–R15 (ASPRS, 2011).
- Intensity normalization shall be strictly linear.
- Common image stretches (minimum-maximum, standard deviations, percent clip, histogram, and so forth) are expressly forbidden.

Nominal Pulse Spacing

For further explanation of ANPD and ANPS, see Lidar Base Specification v. 1.3.

- The required ANPS and ANPD by QL are listed in table 1.
- Aggregate Nominal Pulse Density (ANPD) and Aggregate Nominal Pulse Spacing (ANPS) shall meet the requirements of the Quality Level (QL) of the project with a minimum of QL2 for 3DEP collections.
- Aggregate Nominal Pulse Density (ANPD) shall be no less than 2 points per square meter (QL2); assessment to be made against single swath, first return data located within the geometrically usable center portion (typically ~95%) of each swath.
- Aggregate Nominal Pulse Spacing (ANPS) shall be no greater than 0.70 meters (QL2); assessment to be made against single swath, first return data located within the geometrically usable center portion (typically ~95%) of each swath.
- Dependent on the local terrain and land cover conditions in a project, a greater pulse density may be required on specific projects.

Data Voids

- A data void is considered to be any area greater than or equal to $(4 \times ANPS)^2$, which is measured using first returns only.
- Data voids within a single swath are not acceptable, except in the following circumstances:
    - where caused by waterbodies;
    - where caused by areas of low near infrared reflectivity, such as asphalt or composition roofing;
    - where caused by lidar shadowing from buildings or other features; or
    - where appropriately filled in by another swath.
- For projects designed to achieve the required ANPS through multiple coverage, the entire DPA shall be covered with the designed number of swaths. Areas meeting the size threshold defined above for single coverage that are not covered by the designed number of swaths are data voids.

Spatial Distribution and Regularity

The process described in this section relates only to regular and uniform point distribution. The process does not relate to, nor can it be used for, the assessment of NPS, ANPS, or data voids.

- The spatial distribution of geometrically usable points will be uniform and regular.
- Collections will be planned and executed to produce an aggregate first return point data that approaches a uniform, regular lattice of points.
- The regularity of the point pattern and density throughout the dataset is important and will be assessed by using the following method:
    - Assess only nonwithheld, first return points of a single File Source ID.
    - Exclude acceptable data voids previously identified in this specification.
    - Generate a density raster from the data with a cell size equal to twice the design ANPS.
    - Populate the raster using a count of points within each cell.
    - Ensure that at least 90 percent of the cells in the grid contain at least one lidar point.
- The USGS–NGP may allow lower passing thresholds for this requirement in areas of substantial relief where maintaining a regular and uniform point distribution is impractical.

Collection Conditions

- Atmospheric conditions shall be cloud and fog free between the aircraft and ground during all collection operations.
- Ground conditions will be snow free. Very light, undrifted snow may be acceptable with prior approval.
- Ground conditions shall be free of extensive flooding or any other type of inundation.
- Leaf-off vegetation conditions are preferred.
- Penetration to the ground shall be adequate to produce an accurate and reliable bare-earth surface for the prescribed QL.
- Collections planned for leaf-on collections shall be approved by the USGS–NGP/3DEP prior to issuance of a task order or contract.

Data Processing and Handling

ASPRS LAS File Format

All point deliverables shall be in LAS format, version 1.4-R15, using Point Data Record Format 6, 7, 8, 9, or 10. Data producers are encouraged to review the LAS specification version 1.4–R15 in detail (ASPRS, 2011).

Full Waveform

- If full waveform data are recorded during collection, the waveform packets shall be delivered.
- LAS deliverables, including waveform data, shall use external auxiliary files with the extension .wdp to store waveform packet data. *See* LAS specification version 1.4–R15 (ASPRS, 2011) for additional information.

Time of Global Positioning System Data

- GPS data shall be recorded as Adjusted GPS Time (Standard [satellite] GPS time minus $1*10^9$) at a precision sufficient to allow unique timestamps for each pulse.
- The encoding tag in the LAS header shall be properly set. *See* LAS specification version 1.4–R15 (ASPRS, 2011) for additional information.

Datums

- All data collected shall be tied to the datums listed below:

1. For the CONUS, unless otherwise specified by the user and agreed to in advance by the USGS–NGP:
    - The horizontal datum for latitude and longitude and ellipsoid heights will be the North American Datum of 1983 (NAD 83) using the most recent NGS-published adjustment (currently NAD 83, epoch 2010.00, realization of 2011).
    - The vertical datum for orthometric heights will be the North American Vertical Datum of 1988 (NAVD 88).
    - The geoid model used to convert between ellipsoid heights and orthometric heights will be the latest hybrid geoid model of NGS, supporting the latest realization of NAD 83 (currently [2017] GEOID model).
2. For Alaska, American Samoa, Commonwealth of the Northern Mariana Islands, Guam, Hawaii, Puerto Rico, U.S. Virgin Islands, and other areas:
    - USGS–NGP and all collection partners shall agree to and specify horizontal and vertical datums, ellipsoids, and geoids in advance of data collection.

Coordinate Reference System

- Lidar data and all related or derived data and products shall be processed and delivered in a single CRS agreed upon in advance of data collection by the USGS–NGP and all project partners and cooperators.
- The complete CRS definition and its WKT representation, both horizontal and vertical, shall be documented as part of the agreement.
- In all cases, the CRS used shall be recognized and published by the European Petroleum Survey Group (EPSG).
- Each project shall be processed and delivered in a single CRS, except in cases where a project area covers multiple CRSs such that processing in a single CRS would introduce unacceptable distortions in part of the project area. In such cases, the project area is to be split into subareas appropriate for each CRS. The following requirements apply to the subareas:
    - Each subarea shall be processed and delivered as a separate subproject with its own CRS.
    - All requirements for a single project will apply to each subproject.

  - The DPA boundaries of adjacent subareas shall have topologically coincident boundaries along their common borders.
  - For each project or subarea, all spatial data within the area shall be in the same CRS.
  - An additional CRS delivery, arranged in advance, may also be required on specific projects.

Well-Known Text

- CRS information in LAS files shall use WKT as defined in OGC (2001). All other WKT specifications, including Esri, ISO, and OGC (2015) are expressly forbidden.
- The CRS information may be recorded in either a variable length record (VLR) or an extended variable length record (EVLR) at the discretion of the data producer.
- The CRS record shall contain no whitespace unless enclosed within double quotation marks.
- The CRS record shall contain no carriage returns (CRs), line feeds (LFs), or new lines (NLs), or any other special, control, or nonprintable characters.
- For verification or generation of properly formatted WKT, the USGS recommends the use of the gdalsrsinfo (http://www.gdal.org/gdalsrsinfo.html) tool. gdalsrsinfo is a command line tool that can be downloaded and installed using the OSGeo4W installer (https://trac.osgeo.org/osgeo4w/). The following command will produce WKT that the USGS considers to have valid form:

  $ gdalsrsinfo -o wkt "EPSG:<code>"

  However, the USGS recommends four exceptions to the gdalsrsinfo output:
  - gdalsrsinfo adds an EXTENSION[] tag to capture geoid information in the VERT_DATUM[] section that is not defined in the WKT specification. Data providers shall remove the EXTENSION[] tag if it is shown.
  - In cases where the datum name output from gdalsrsinfo differs from that listed in the EPSG Registry database (http://www.epsg-registry.org), the USGS would prefer that the name be changed to match the EPSG Registry; however, the GDAL output will be accepted. For example, EPSG:1116 is named "NAD83_National_Spatial_Reference_System_2011" in the output from GDAL but the name on EPSG Registry is "NAD83 (National Spatial Reference System 2011)" and the only listed alias is "NAD83(2011)"
  - For all projected coordinate systems, the USGS recommends WKT (OGC, 2001) default values: AXIS["X",EAST], AXIS["Y",NORTH]; however, the GDAL output ("Easting" and "Northing" rather than "X" and "Y") will be accepted.
  - gdalsrsinfo and EPSG outputs use "metre" instead of the U.S. convention "meter." Either spelling is acceptable to the USGS.
- The USGS recognizes that the GDAL tool is not a rigorous standards-based solution, but it is a mutually convenient open source tool suitable for 3DEP purposes at this time. Following are the USGS directions for specific WKT format and content:
  - The vertical CRS shall be included in the CRS.
  - The geoid name shall be appended to the VERT_CS[] name field. For example: VERT_CS["NAVD88 height (ftUS) - GEOID18"].
  - Horizontal and vertical CRS shall be wrapped within a COMPD_CS.
  - The EPSG AUTHORITY[] tag shall not be included for the compound coordinate system.
  - User-defined entities will not be allowed for capturing geoid information in the WKT (for example, GEOID_MODEL[]). These nonstandard entity entries are not consistently machine readable.

- All elements of the CRS record shall include the EPSG AUTHORITY[] entry and a valid EPSG code, except where no EPSG code exists for the element or where otherwise excluded from this requirement within this specification.
- A given LAS file may contain any number of CRS entries, as VLRs and (or) EVLRs in any combination, as WKT and (or) GeoTIFF in any combination, regardless of the PDRF, provided that:
  - ALL entries shall be tagged as "Superseded"—EXCEPT for the single valid entry to be used. *See* LAS specification version 1.4–R15 (ASPRS, 2011) for further details.
  - The single valid entry shall be compliant WKT (OGC, 2001).
  - The global encoding bit for CRS shall be set to 1.

- The geoid model used to convert elevations from the ellipsoid to orthometric heights shall also be identified in the <lidar><ldrinfo><ldrgeoid> tag within the Federal Geographic Data Committee (FGDC) metadata files.
- The NGS model filename shall be recorded (for example, <ldrgeoid>g2018u0.bin</ldrgeoid>).

Units of Reference

- All references to the units of measure "Feet" and "Foot" shall specify "International," "Intl," "U.S. Survey," or "US."

File and Point Source Identification

- At the time of its creation and prior to any further processing each swath shall be assigned a unique file source ID.
- Each point within the swath shall be assigned a point source ID equal to the file source ID.
- The point source ID on each point shall be persisted unchanged throughout all processing and delivery.
- The file source ID for tiled LAS files shall be set to 0. *See* LAS specification version 1.4–R15 (ASPRS, 2011).

Positional Accuracy Validation

- Prior to classification and development of derivative products from the point data, the absolute and relative vertical accuracy of the point data shall be verified and a detailed report of the validation processes used shall be delivered.

Absolute Horizontal Accuracy

- The horizontal accuracy of each lidar project shall be reported using the form specified by the ASPRS (2014): "This data set was produced to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a ___ (cm) RMSEx / RMSEy Horizontal Accuracy Class which equates to Positional Horizontal Accuracy = +/- ___ cm at a 95% confidence level."

Relative Vertical Accuracy

- Relative vertical accuracy refers to the internal geometric quality of a lidar dataset without regard to surveyed ground control. Two primary factors need to be considered in lidar data vertical accuracy:

Intraswath Precision (smooth surface precision)

- Precision will be calculated as:

  Precision = *Range* - (*Slope* x *Cellsize* x 1.414)

  where:

  Precision, Range, and Slope are rasters (square cells assumed);

Range	is the difference between the highest and lowest lidar points in each pixel;
Slope	is the maximum slope of the cell to its 8 neighbors, expressed as a decimal value, calculated from the minimum elevation in each cell; and
CellSize	is the edge dimension of the cell.
1.414	is the factor to compute the diagonal dimension of the pixel.

CellSize is set to the ANPS, rounded up to the next integer, and then doubled:

$$Cellsize = CEILING(ANPS) \times 2$$

where:

CEILING is a function to round *ANPS* up to the next integer.

- Assessment of precision will be made on hard surfaced areas (for example, parking lots or large rooftops) containing only single return lidar points.
- Sample areas for assessment of precision will be approximately 100 pixels.
- To the degree allowed by the data and the project environment, multiple sample areas representing the full width of the swath(s) (left, center, and right) will be examined.
- Multiple single swaths from a single lift may be used if needed to sample the full swath width.
- At a minimum, precision shall be assessed against for each lift of each aircraft/instrument combination used on the project. Additional areas may be checked at the discretion of the USGS–NGP.
- Each test area will be evaluated using a signed difference raster with a cell size equal to the ANPS, rounded up to the next integer, then doubled (*Cellsize*=*CEILING*(*ANPS*)×2).
- The difference rasters will be statistically summarized to verify that root mean square difference in the z direction ($RMSD_z$) values do not exceed the limits set forth in table 2 for the QL of information that is being collected.
- Precision shall be reported by way of a polygon shapefile delineating the sample areas checked and, using the cells within each polygon as sample values, attributed with:
  - minimum slope-corrected range (numeric),
  - maximum slope-corrected range (numeric),
  - and $RMSD_z$ of the slope-corrected range (numeric).

Interswath (Overlap) Consistency

- Overlap consistency will be assessed at multiple locations within overlap in nonvegetated areas of only single returns and with slopes of less than 10 degrees.
- To the degree that the data allow, test areas should be located such that the full width of the overlap is represented.
- The overlap areas that will be tested are those between the following:
  (1) adjacent, overlapping parallel swaths within a project;
  (2) cross-tie swaths and a sample of intersecting project swaths in both flight directions; and
  (3) adjacent, overlapping lifts.
- Each overlap area will be evaluated using a signed difference raster with a cell size equal to the ANPS, rounded up to the next integer, then doubled (*Cellsize*=*CEILING*(*ANPS*)×2).
- The difference rasters will be statistically summarized to verify that $RMSD_z$ values do not exceed the limits set forth in table 2 for the QL of information that is being collected.

- The interswath consistency shall be reported by way of a polygon shapefile delineating the sample areas checked and, using the cells within each polygon as sample values, attributed with:
  (1) minimum difference in the sample area (numeric),
  (2) maximum difference in the sample area (numeric), and
  (3) $RMSD_z$ of the sample area (numeric).

Check Points

Data producers are encouraged to carefully review the requirements in the "Positional Accuracy Standards for Digital Geospatial Data" (ASPRS, 2014).

- Check points for NVA assessments shall be surveyed in clear, open areas (which typically produce only single lidar returns) devoid of vegetation and other vertical artifacts (such as boulders, large riser pipes, and vehicles).
- Check points shall not be located on ground that has been plowed or otherwise disturbed.
- The same check points may be used for NVA assessment of the point data and DEM.
- Check points for VVA assessments shall be surveyed in vegetated areas (typically characterized by multiple return lidar).
- Check points will be located in areas having a minimum homogeneous area of $(ANPS*5)^2$, with less than one-third of the required $RMSE_z$ deviation from a low-slope (<10 degree) plane.
- In land covers other than forested and dense urban, the tested check point will have no obstructions above 15 degrees over the horizon.
- All tested locations will be photographed showing the position of the survey tripod and the ground condition of the surrounding area.
- Control points used in the calibration process for data acquisition shall not be used as check points.
- Check points shall be an independent set of points used for the sole purpose of assessing the vertical accuracy of the project.
- Every checkpoint used to assess absolute vertical accuracy shall have a corresponding ground photograph with the following requirements:
  - Photographs shall be captured at the time of the checkpoint survey.
  - Photographs shall be taken from each of the cardinal points (North, South, East, and West).
  - GPS survey equipment shall be in view so that the surrounding environment is recorded with respect to the point location being collected.
  - Photos shall be taken during daylight hours.
  - Photographs shall be of sufficient spatial resolution to enable interpretation of terrain undulations and vegetative cover surrounding the checkpoint for a minimum of 10 feet in all directions surrounding checkpoint.
  - All photographs shall be embedded and delivered in a single PDF document, preferably in the ground survey report.
  - Each photograph shall be labeled in the PDF with the checkpoint ID so that it can be readily located.
- The quantity and location of check points shall meet the following requirements, unless alternative criteria are approved by the USGS–NPG in advance (*see* ASPRS [2014] for additional information):
  1. The ASPRS-recommended total number of check points for a given project size shall be met.
  2. The ASPRS-recommended distribution of the total number of check points between NVA and VVA assessments shall be met.

3. Check points within each assessment type (NVA and VVA) will be well-distributed across the entire project area. *See* “Glossary” section at the end of this specification for a definition of “well-distributed.”
4. Within each assessment type, check points will be distributed among all constituent land cover types in approximate proportion to the areas of those land cover types (ASPRS, 2014).

Absolute Vertical Accuracy

- Absolute vertical accuracy of the lidar data and the derived DEM will be assessed and reported in accordance with ASPRS (2014) .
- Vegetated and nonvegetated land cover types shall be assessed for absolute vertical accuracy.
- Federal Emergency Management Agency (2003) identifies seven land cover types; National Digital Elevation Program (2004) and ASPRS (2004) reiterate the first five of those types. The way in which each of the seven classes was reported under the previous standards and how they are reported under the new ASPRS standards and by this specification are shown in table 3.
- Four absolute accuracy values shall be assessed and reported:
    1. NVA for the point data.
    2. VVA for the point data.
    3. NVA for the DEM.
    4. VVA for the DEM.
- The minimum NVA and VVA requirements for all data, using the ASPRS methodology, are listed in table 4. Both the NVA and VVA required values shall be met.
- NVA for the point data shall be assessed by comparing check points surveyed for NVA assessment (see Check Points) to a triangulated irregular network (TIN) constructed from ground-classified lidar points in those areas.
- VVA for the point data shall be assessed by comparing check points surveyed for VVA assessment (see Check Points) to a triangulated irregular network (TIN) constructed from ground-classified lidar points in those areas.
- NVA and VVA for the DEM are assessed by comparing check points to the final bare-earth surface.
- The minimum required thresholds for absolute and relative accuracy may be increased by the USGS–NGP when any of the following conditions are met:
    - A demonstrable, substantial, and prohibitive increase in cost is needed to obtain this accuracy, which is often the case in heavily vegetated project areas.
    - An alternate specification is needed to conform to previously contracted phases of a single larger overall collection effort such as for multiyear statewide collections.
    - The USGS–NGP agrees that the use of an alternate specification is reasonable and in the best interest of all stakeholders.

Use of the LAS Withheld Bit Flag

- The withheld bit flag, as defined in LAS specification version 1.4–R15 (ASPRS, 2011), shall be used to identify points that cannot be reasonably interpreted as valid surface returns. Examples include outliers, blunders, geometrically unreliable points, aerosol back-scatter, laser multi-path, airborne objects, and sensor anomalies.
- The withheld flag may be used in conjunction with other classification codes (low/high noise for example), but it should be used in all cases where the previously mentioned criteria are met.

Use of the LAS Overage (Overlap) Bit Flag

- If overage points must be excluded to produce a uniform DEM then those overage points shall be identified using the LAS overlap bit flag in all point cloud deliverables. *For more information on the difference between overlap and overage, refer to figures 4–5 (at the back of the report)* *and the "Glossary" section. Identification of overage points allows their simple exclusion from subsequent processes where the increased density and elevation variability they introduce is unwanted (that is, DEM generation).*

Point Classification

- The minimum, required classification scheme for lidar data is found in table 5.
- All points that fall within the minimum classification scheme (table 5) and not flagged as withheld shall be properly classified.
- Additional classes may be used on specific projects.
- Accuracy of point classification into classes beyond the minimum scheme (table 5) will not be assessed by the USGS, as documented in metadata.
- Assessing and verifying accuracy of point classification into classes beyond the minimum scheme will be the responsibility of the partner requesting the additional classes.
- No points in the classified LAS deliverable may remain assigned to Class 0, unless these points are flagged as withheld.
- Points classified as water will only be checked when associated with a breakline.
- If it is necessary to identify overage points in overlap areas, the overage points shall be identified using the overlap bit flag as defined in LAS Specification Version 1.4-R15 (ASPRS, 2011).
- No classification code may be used to identify points as overage points.
- Model key points, if calculated, shall be identified using the key point bit flag as defined in LAS specification version 1.4–R15 (ASPRS, 2011). Model key points may, in addition, be identified using class 8 at the discretion of the data producer.

Classification Consistency

- Point classification is to 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.

Tiles

- A single nonoverlapping project tiling scheme will be established and agreed upon by the data producer and the USGS–NGP before collection.
- The tiling scheme will be used for all tiled deliverables:
    - The tiling scheme shall use the same coordinate reference system and units as the data.
    - The tile size shall be an integer multiple of the cell size for raster deliverables.
    - The tiles shall be indexed in *x* and *y* to an integer multiple of the *x* and *y* dimensions of the tile.
    - The tiled deliverables shall edge-match seamlessly and without gaps.
    - The tiled deliverables shall conform to the project tiling scheme without added overlap.

Point Duplication

- Duplication of lidar points (*x*, *y*, *z*, and *timestamp*) within the project is not acceptable. LAS files containing duplicated points will be rejected. Near duplication (that is, a group of points duplicated but with a slight but consistent spatial offset) will be regarded as duplication.

Deliverables

- Delivery is required for all ancillary products that support the processing of the lidar dataset including, but not limited to, imagery and all metadata associated with those data.

Metadata

- Product metadata files shall comply with the Federal Geographic Data Committee (FGDC) "Content Standard for Digital Geospatial Metadata" (CSDGM) (FGDC, 1998).
- Metadata deliverables shall include the following:
    - A survey report detailing the collection of all ground survey data including the following:
        - Control points used to calibrate and process the lidar and derivative data.
        - Check points used to validate the lidar point data or any derivative product.
    - A collection report detailing mission planning and including detailed flight logs. Flight logs are expected to include:
        - A unique ID for each lift.
        - The take-off and landing times for each lift.
        - The aircraft make, model, and tail number.
        - The instrument manufacturer, model, and serial number.
        - The date of the instrument's most recent factory inspection/calibration.
        - General weather conditions.
        - General observed ground conditions.
        - All inflight disturbances and notable head/tail/crosswinds.
        - All inflight instrument anomalies and any inflight changes in settings.
    - A processing report detailing:
        - Calibration and instrument settings by lift and identified by the lift ID.
        - Classification methods.
        - Product generation procedures including methodology used for breakline collection and hydro-flattening (*see* the "Hydro-Flattening" section and appendix 2 for more information on hydro-flattening).
    - A QA/QC report, detailing procedures for analysis, accuracy assessment, and validation of the project data, including the following [*NOTE: The following four reports may be compiled as separate documents, or combined into a single document, at the discretion of the data producer*]:
        - The expected horizontal accuracy of the lidar data, as described in ASPRS (2014).
        - The assessed relative vertical accuracy of the point data (smooth surface repeatability and overlap consistency). Relative vertical accuracy requirements are listed in table 2.
        - The assessed NVA of the unclassified lidar data in accordance with the guidelines set forth in ASPRS (2014). Absolute vertical accuracy requirements for the unclassified point data using the ASPRS methodology are listed in table 4.
        - The assessed NVA and VVA of the bare-earth surface in accordance with the guidelines set forth in ASPRS (2014). Absolute vertical accuracy requirements using the ASPRS methodology for the bare-earth DEM are listed in table 4.
        - QA/QC analysis materials for the absolute vertical accuracy assessment.
    - A georeferenced, polygonal representation of the detailed extents of each lidar swath collected, as a GIS layer. The goal is a set of polygons that define the area actually covered by the swaths, not merely the points collected in the swaths.
        - The extents shall be those of the actual coverage of the collected swath, exclusive of peripheral TIN artifacts:
            - Minimum bounding rectangles or simplified rectangles are not acceptable.

        - The boundary will generally follow the overall shape of the swath.
      - Each swath polygon shall be attributed with the following:
        - The lift's unique ID (string format).
        - The unique Point Source ID of the swath (string format).
        - The type of swath:
          - "Project,"
          - "Cross-tie,"
          - "Fill-in,"
          - "Calibration," or
          - "Other" (string format).
        - Start time in adjusted GPS seconds to the nearest integer.
        - End time in adjusted GPS seconds to the nearest integer.
      - Esri polygon shapefile or geodatabase or geopackage is required. Geopackage is preferred.
    - A georeferenced, digital spatial representation of the detailed extents of each delivered dataset.
      - The extents shall be those of the actual lidar source or derived product data, exclusive of peripheral TIN artifacts or raster NODATA areas.
      - A union of tile boundaries or minimum bounding rectangles is not acceptable.
      - For the point datas, no line segment in the boundary will be longer than the four times the ANPS from the nearest lidar point.
      - Esri polygon shapefile or geodatabase is required.
    - Product metadata (FGDC compliant, XML format metadata).
      - One XML file is required for each of the following deliverable product groups:
        - Classified point data.
        - Bare-earth DEMs.
        - Breaklines.
        - Any other datasets delivered (digital surface models [DSM], intensity images, height above ground surfaces, and others).
      - Metadata files for individual data files within a deliverable product group are acceptable but are not required.
      - FGDC-compliant metadata shall pass the USGS Metadata Parser (MP) without errors.
- Swath Separation Images
    - **Description:** Swath separation images (figure 6) use color-coding to illustrate differences in elevation (z-) values where swaths overlap. The color-coded images are semi-transparent and overlay the lidar intensity image. They are ancillary metadata used as visual aids to more easily identify regions within point cloud datasets that may have suspect interswath alignment or other geometric issues. These images may be produced by a variety of methods; however, their usefulness will be ensured by following the specification requirements and documenting the processes used to create the images in the lidar acquisition and processing report.
    - Image Creation:
      a. All returns shall be used to create the images.
      b. All point classes and flags shall be enabled when creating the images and points flagged as withheld or classified as noise shall be excluded.

    c. Elevation values and differences shall not be subjected to a threshold or otherwise clipped so all differences are represented.
    d. The images will be derived from TINs to reduce the number of false difference values on slopes; however, other algorithms are acceptable.
    e. The images shall consist of a 50 percent transparent RGB layer overlaying the lidar intensity image.
    f. The images shall use at least three color levels wherever two or more swaths overlap within a pixel.
    g. Where two or more swaths overlap within a pixel (based on point source ID),
        i. pixel color shall be based on vertical difference of swaths using the following breaks (based on multiples of the Swath Overlap Difference for the QL):
            1. 0-8 cm: GREEN;
            2. 8-16 cm: YELLOW;
            3. > 16 cm or > last additional color ramp bin value: RED (for example, addition of ORANGE pixels for the range of 16-24 cm would require red pixels to represent > 24 cm).
        ii. color choice of green, yellow, and red is suggested but not required.
        iii. no pixel shall remain uncolored (transparent) in the overlap areas.
    h. Where swaths do not overlap, pixel values shall be intensity alone.
  - Image file formats and version control:
    a. Swath difference image format may be delivered as GeoTIFF or JPEG (with world file) by tile or as a single compressed JPEG 2000 (JP2) image mosaic.
    b. The point cloud geometry and intensity data delivered shall be identical to the point cloud geometry and intensity data used to create the difference images. Changes in the point cloud geometry or intensity requires recreation of the difference images.
  - Spatial extent and coordinate reference system:
    a. Spatial resolution (pixel dimension) of the images shall be between 2 and 4 times the Nominal Pulse Spacing (2-4 x NPS) in the project's linear unit (meters or feet).
    b. The difference images must be representative of the associated data delivery.
    c. The images shall be in the same CRS as the point cloud data to ensure alignment with the point cloud.
- A block of lidar-related metadata tags specified by the USGS shall be included in the CSDGM (FGDC, 1998) metadata files for all lidar data deliverables. All tags are required.
- Tags requiring a numeric value shall not contain text (that is, units) because the required reporting units are defined in the appendix 4. The descriptive template of this lidar metadata block is provided in appendix 4 and a completed example is provided in appendix 3.

Classified Point Data

- Unless waived through a pre-collection agreement with the NGP and noted clearly in the task order, delivery of classified point data is a requirement for USGS–NGP lidar projects. Classified point data deliverables shall include or conform to the following procedures and specifications:
  - All project swaths, returns, and collected points shall be fully calibrated, adjusted to ground, classified, and segmented into tiles. Project swaths exclude calibration swaths, cross-ties, and other swaths not used, and not intended to be used, for product generation.
  - LAS Specification version 1.4, PDRF 6, 7, 8, 9, or 10.

- Overage (Overlap) and Withheld flags set as appropriate.
- If collected, waveform data in external auxiliary files with the extension .wdp. *See* LAS specification version 1.4–R15 (ASPRS, 2011) for additional information.
- Correct and properly formatted georeference information as WKT (OGC, 2001) included in all LAS file headers.
- GPS times recorded as Adjusted GPS Time at a precision sufficient to allow unique timestamps for each pulse.
- Intensity values, normalized to 16-bit. *See* LAS specification version 1.4–R15 (ASPRS, 2011) for additional information.
- Tiled delivery, without overlap, using the project tiling scheme.
- Classification, as defined in table 5, at a minimum.

Bare-Earth Surface (Raster Digital Elevation Model)

- Delivery of a hydro-flattened bare-earth topographic DEM is a requirement for all USGS–NGP lidar projects. Specific research projects may be exempt from some or all these requirements. Bare-earth surface deliverables shall include or conform to the following procedures and specifications:
  - Bare-earth DEM, generated to the limits of the DPA.
  - DEM resolution as shown in table 6.
  - 32-bit floating-point GeoTIFF raster format.
  - The NODATA value of '-999999' shall be defined in GDAL_NODATA tag #42113.
  - GDAL version 2.4.0, or as otherwise agreed to in advance and specified in the Task Order, shall be used to populate GeoTIFF keys and tags.
  - Additional requirements for GeoTIFF tiling, compression, and internal overviews may be referenced in Task Orders.
  - DEM data shall be in the same CRS as the lidar data.
  - Georeference information in or accompanying each raster file, as appropriate for the file format. This information shall include both horizontal and vertical systems; the vertical system name shall include the geoid model used to convert from ellipsoid heights to orthometric heights.
  - Tiled delivery without overlap.
  - DEM tiles with no edge artifacts or mismatch. A quilted appearance in the overall DEM surface will be cause for rejection of the entire DEM deliverable, whether the variations are caused by differences in processing quality or character among tiles, swaths, lifts, or other artificial divisions.
  - Void areas coded using a NODATA value of ‘-999999’ and shall be defined in GDAL_NODATA tag #42113.
  - Hydro-flattening as outlined in the “Hydro-Flattening” section. Depressions (sinks), whether natural or man-made, are not to be filled (as in hydro-conditioning). The methodology used for hydro-flattening is at the discretion of the data producer (refer to appendix 2 for more information on hydro-flattening).
  - Bridges removed from the surface (refer to the “Glossary” section for the definition of “bridge”).
  - Road or other travel ways over culverts remain intact in the surface (refer to the “Glossary” section for the definition of a culvert).
  - A report on the assessed absolute vertical accuracy of the bare-earth surface in accordance with the guidelines set forth in ASPRS (2014). Absolute vertical accuracy requirements using the ASPRS methodology for the bare-earth DEM are listed in table 4.

- QA/QC analysis materials used in the assessment of absolute accuracy.

Breaklines

- Delivery of all breaklines collected on or used in support of the project is required for USGS–NGP lidar projects. This includes breaklines used for bridge and saddle treatments and any additional breaklines required by project cooperators.
- Breaklines representing all hydro-flattened features in a project, regardless of the method used for hydro-flattening, are required for USGS–NGP lidar projects. Specific research projects may be exempt from these requirements with prior approval of the USGS–NGP.
- Breakline deliverables shall include or conform to the following procedures and specifications:
    - Breaklines developed to the limit of the DPA.
    - Breaklines delivered in shapefile or file geodatabase formats, as PolylineZ and PolygonZ feature classes, as appropriate to the type of feature represented and the methodology used by the data producer.
    - Breakline data shall be in the same CRS as the lidar data.
    - Each breakline feature class shall have properly formatted, accurate, and complete georeferenced information stored in the format's standard file system location. Each shapefile shall include a correct and properly formatted .prj file. All CRS information for 3-dimensional (3D) data shall include the vertical reference and identify the geoid model used to convert from the ellipsoid to orthometric heights.
    - EleHydro breakline data will conform to the requirements defined in the "EleHydro Breakline GIS Data Dictionary" section (*See* LBS v. 1.3 for EleHydro breakline information).
    - Breakline delivery may be in a single layer or in tiles, at the discretion of the data producer. In the case of tiled deliveries, all features shall edge-match exactly across tile boundaries in both the horizontal (*x*, *y*) and vertical (*z*) spatial dimensions.
    - Delivered data shall be sufficient for the USGS to effectively recreate the delivered DEMs using the lidar points and breaklines without substantial editing.

Digital Elevation Model Surface Treatments

Bridges

- All instructions and requirements regarding the use of breaklines also applies to non-hydrographic terrain generation below bridges.
- Any breaklines used to enforce a logical terrain surface below a bridge shall be considered a required deliverable.
- The bare-earth surface below the bridge shall be a continuous, logical interpolation of the apparent terrain lateral to the bridge deck.
- Where abutments are clearly visible, the bare-earth interpolation shall begin at the junction of the bridge deck and approach structure. Where this junction is not clear, the contractor shall use their best judgement to delineate the separation of below-bridge terrain from elevated bridge surface.
- Streams, rivers, and water bodies meeting the criteria for hydro-flattening shall be monotonically continuous where bridge decks have been removed.
- Bridges, as defined in the glossary, shall be removed from the bare-earth surface.

Hydro-Flattening

- Hydro-flattening pertains only to the creation of derived DEMs from lidar points and breaklines. Hydro-flattening makes no changes to the geometry of the originally computed lidar points.

Breaklines developed for use in hydro-flattening may also be used to support classification of the point data.

- Bare-earth lidar points (serving as mass points) that are in close proximity to any breakline shall be classified as Ignored Ground (class 20) and shall be excluded from the DEM generation process when the breaklines are included. This process prevents unnatural surface artifacts from being created between lidar points and breakline vertices. The proximity threshold for reclassification as Ignored Ground is at the discretion of the data producer, but in general should not exceed twice the ANPS.
- The requirements for hydro-flattening are listed below. These requirements also define the minimum features for which breaklines shall be collected and delivered.
    1. Inland Ponds and Lakes
        - Waterbodies with a surface area of 0.8 hectare (ha; 2 acres) or greater (approximately equal to a round pond 100 m in diameter) at the time of collection shall be flattened.
        - Flattened waterbodies shall present a flat and level water surface (a single elevation for every bank vertex defining the waterbody's perimeter).
        - The entire water surface edge shall be at or below the immediately surrounding terrain (the presence of floating waterbodies will be cause for rejection of the deliverable).
        - Long impoundments such as reservoirs, inlets, and fjords, whose water surface elevations decrease with downstream travel, shall be treated as streams or rivers.
    2. Inland Streams and Rivers
        - Streams and rivers of a 30-m or greater nominal width shall be flattened.
        - Streams or rivers whose width varies above and below 30 m will not be broken into multiple segments; data producers will use their best professional cartographic judgment in determining when a stream or river has attained a nominal 30-m width.
        - Flattened streams and rivers shall present a flat and level water surface bank-to-bank (perpendicular to the apparent flow centerline).
        - Flattened streams and rivers shall present a gradient downhill water surface, following the immediately surrounding terrain.
        - In cases of sharp turns of rapidly moving water, where the natural water surface is notably not level bank-to-bank, the water surface will be represented as it exists while maintaining an aesthetic cartographic appearance.
        - The entire water surface edge shall be at or below the immediately surrounding terrain.
        - Stream channels shall break at culvert locations leaving the roadway over the culvert intact.
        - Streams shall be continuous at bridge locations.
        - Bridges in all their forms shall be removed from the DEM.
        - When the identification of a structure as a bridge or culvert cannot be made definitively, the feature shall be regarded as a culvert.
    3. Non-Tidal Boundary Waterbodies
        - Boundary waterbodies are waterbodies that contain some or all of the DPA.
        - Boundary waterbodies may be any type of waterbody but are virtually always large in area or width.

- A boundary waterbody shall be represented as a polygon that follows the shore throughout the project and is then closed using arbitrary line segments as needed across the waterbody. Boundary waterbodies do not include the natural far shoreline.
- The water surface shall be flat and level, as appropriate for the type of waterbody (level for lakes, gradient for rivers, and so forth). It is not expected that ponds <0.8 ha (2 acres) or streams <30 m in width would be used as boundary waterbodies, thus it is expected that all boundary waterbodies will be hydro-flattened.
- All landward water surface edges shall be at or below the immediately surrounding terrain.
- Unusual changes in the water surface elevation that may take place over the course of the collection (for example, different river stages due to increased or decreased discharge from an upstream dam) shall be documented in the project metadata.
- Unusual changes in water surface elevation shall be handled as described in Tidal Waterbodies.

4. Tidal Waterbodies
    - Tidal waterbodies are defined as any waterbody that is affected by tidal variations, including oceans, seas, gulfs, bays, inlets, salt marshes, and large lakes.
    - Tidal variations during data collection or between different data collections will result in lateral and vertical discontinuities along shorelines. Because it is the USGS–NGP's intent for the DEM to represent as much ground as the collected data permit, lidar ground points are not to be removed for the sake of adjusting a shoreline inland to match another shoreline.
    - Likewise, adjusting a shoreline outland will create an equally unacceptable area of unmeasured land in the DEM. It is recommended that, to the highest degree practical, collections are planned to minimize tidal differences at the land-water interface.
    - In addition to meeting the requirements for inland waterbodies listed in "1. Inland Ponds and Lakes" and "2. Inland Streams and Rivers" (above) as appropriate, the treatment of tidal waterbodies shall also meet the following requirements:
        - Within each tidal waterbody, the water surface shall be flat and level for each different water surface elevation.
        - Vertical discontinuities within a tidal waterbody resulting from tidal variations during the collection are considered normal and shall be retained in the final DEM.
        - Horizontal discontinuities along the shoreline of a tidal waterbody resulting from tidal variations during the collection are considered normal and shall be retained in the final DEM.
        - For projects located in coastal areas, cooperating partners may impose additional requirements for tidal coordination.
5. Islands
    - Permanent islands 0.4 ha (1 acre) (approximately equal to a round island 72 m in diameter) or larger shall be delineated within all waterbodies.

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Tables

Table 1. Aggregate nominal pulse spacing and density.

Quality level	Aggregate nominal pulse spacing (m)	Aggregate nominal pulse density (pls/m^2)
QL0	≤0.35	≥8.0
QL1	≤0.35	≥8.0
QL2	≤0.71	≥2.0
QL3	≤1.41	≥0.5

Table 2. Relative vertical accuracy for light detection and ranging swath data.

Quality level	Smooth surface repeatability, $RMSD_z$ (m)	Swath overlap difference, $RMSD_z$, (m)
QL0	≤0.03	≤0.04
QL1	≤0.06	≤0.08
QL2	≤0.06	≤0.08
QL3	≤0.12	≤0.16

Table 3. Land cover classes.

Class number	Land cover class or description	Previous reporting group	Current reporting group
1	Clear or open, bare earth, low grass; for example, sand, rock, dirt, plowed fields, lawns, golf courses	FVA	NVA
2	Urban areas; for example, tall, dense man-made structures	SVA	NVA
3	Tall grass, tall weeds, and crops; for example, hay, corn, and wheat fields	SVA	VVA
4	Brush lands and short trees; for example, chaparrals, mesquite	SVA	VVA
5	Forested areas, fully covered by trees; for example, hardwoods, conifers, mixed forests	SVA	VVA
6	Sawgrass	n/a	n/a
7	Mangrove and swamps	n/a	n/a

Table 4. Absolute vertical accuracy for light detection and ranging data and digital elevation models.

Quality level	RMSEz (nonvegetated) (m)	NVA at the 95-percent confidence level (m)	VVA at the 95th percentile (m)
QL0	≤0.050	≤0.098	≤0.15
QL1	≤0.100	≤0.196	≤0.30
QL2	≤0.100	≤0.196	≤0.30
QL3	≤0.200	≤0.392	≤0.60

Table 5. Minimum light detection and ranging data classification scheme.

Code	Description
1	Processed, but unclassified
2	Bare earth
7	Low noise
9	Water
17	Bridge deck
18	High noise
20	Ignored ground (*typically breakline proximity*)
21	Snow (*if present and identifiable*)
22	Temporal exclusion (*typically nonfavored data in intertidal zones*)

Table 6. Minimum digital elevation model cell size.

Quality level	Minimum cell size (m)	Minimum cell size (ft)
QL0	0.5	1
QL1	0.5	1
QL2	1	2
QL3	2	5

Figures

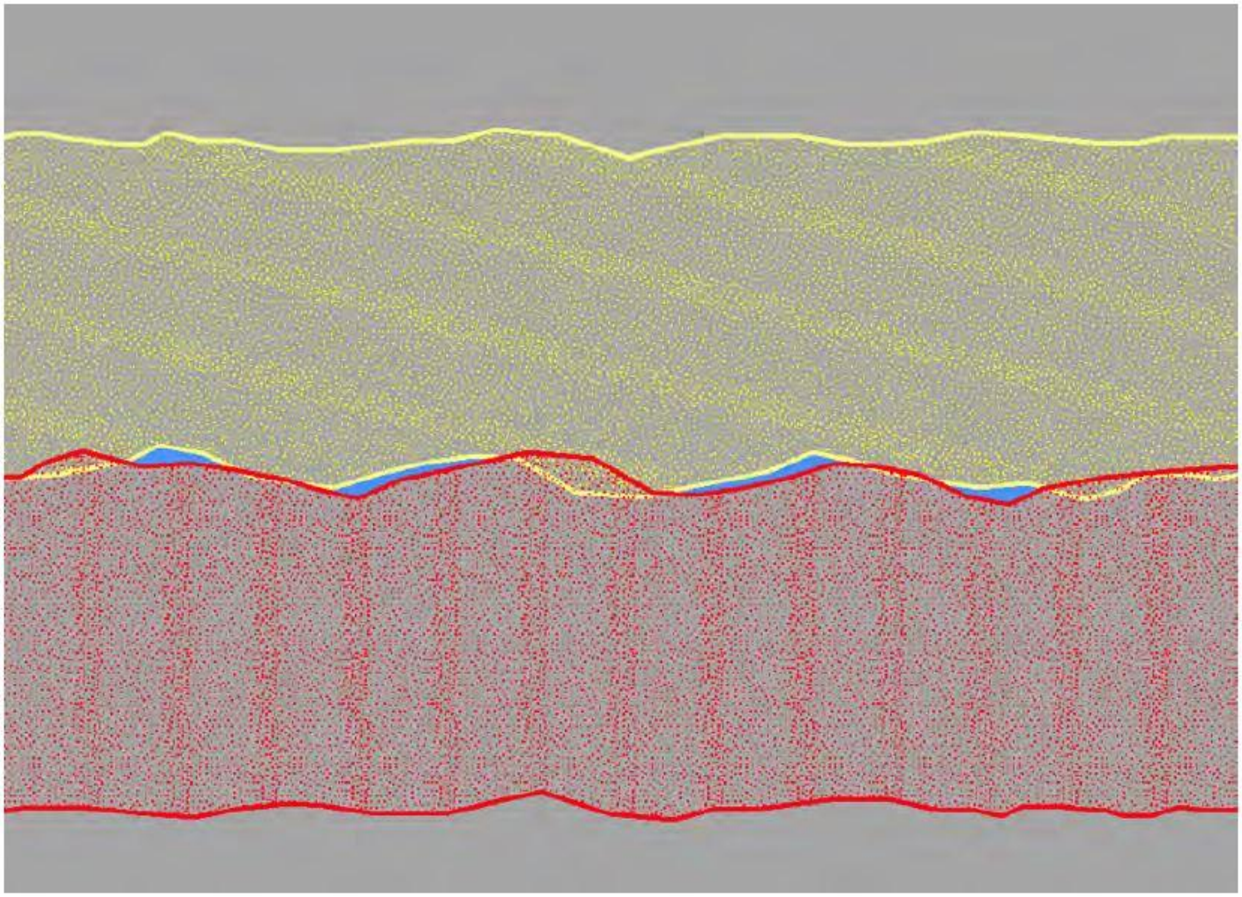

Figure 1. Single coverage collection, no overlap. Adjacent swaths (red and yellow) in this example have been collected with insufficient overlap, causing gaps in coverage. The blue areas depict data voids, which are grounds for rejection of the project.

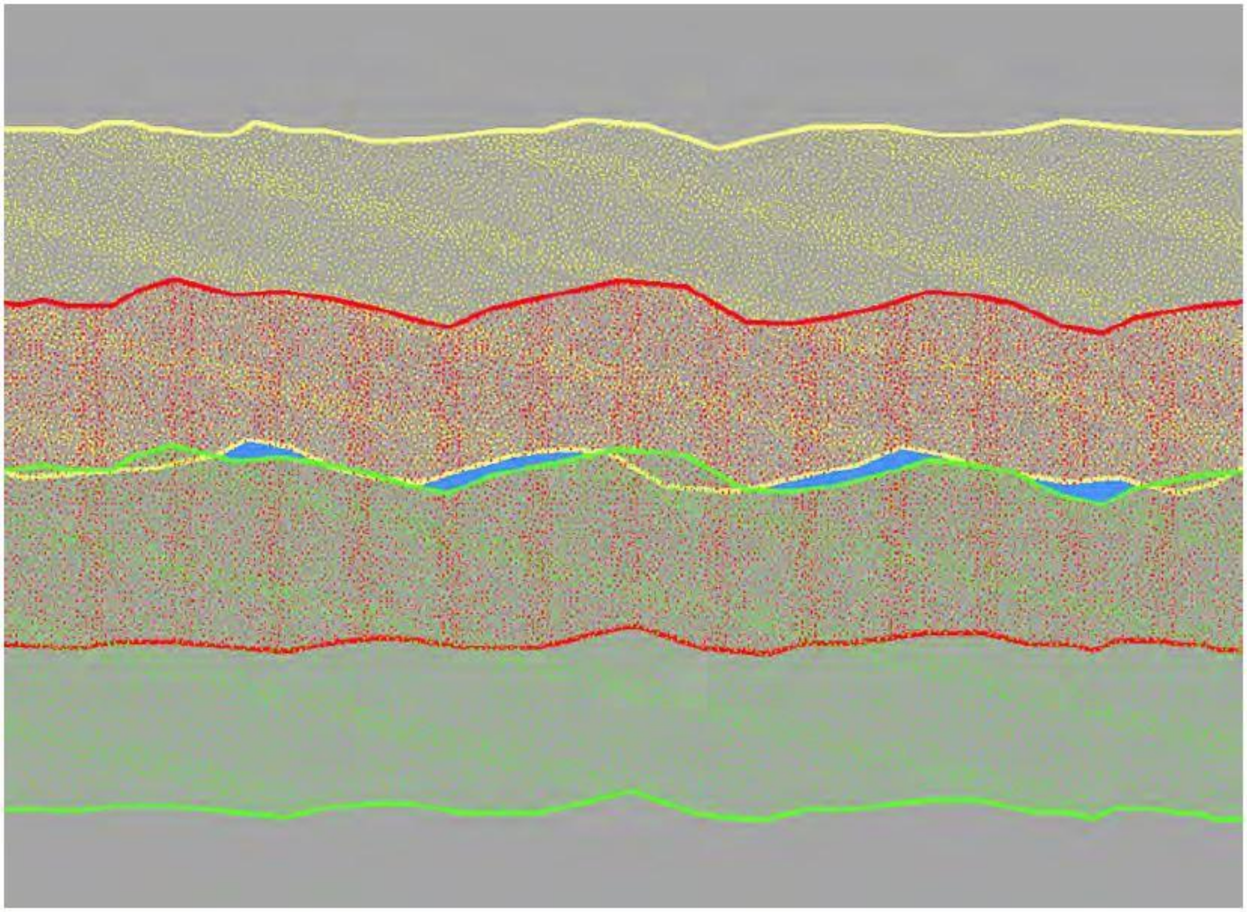

Figure 2. Designed double coverage collection, 50-percent overlap. In this example, three adjacent overlapping swaths (green, red, and yellow) have been collected. Because the design of the project achieved the required aggregate nominal pulse density (ANPD) through double-coverage, the blue areas that are not covered by two swaths are considered data voids, which are grounds for rejection of the project.

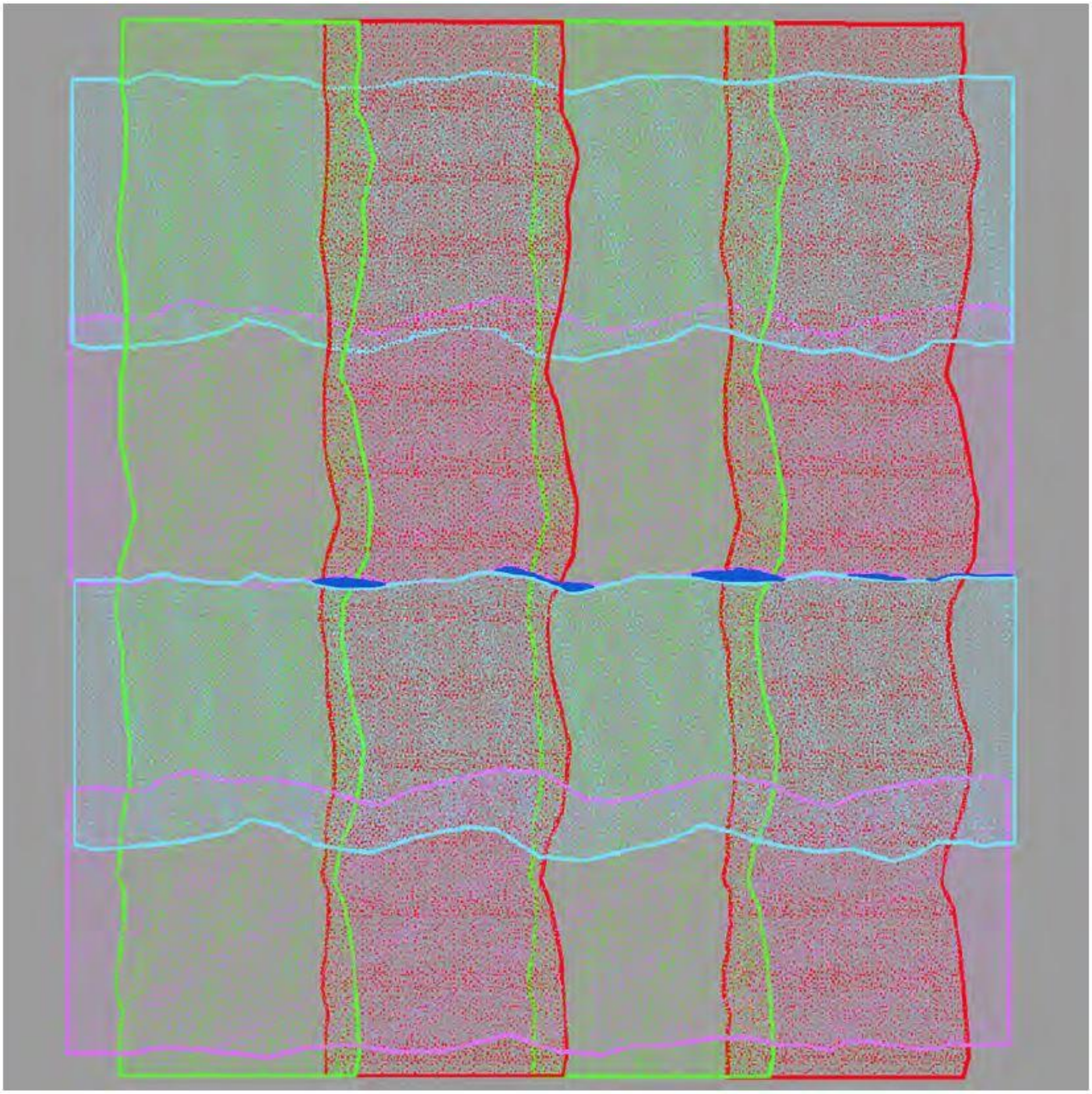

Figure 3. Designed double coverage collection, cross-flights with 20-percent overlap. Four overlapping swaths, shown in green, red, cyan, and magenta are shown in this example. The lower cyan swath was erroneously flown too far south, causing the data voids shown in blue. Because the design of the project was to achieve the required aggregate nominal pulse density through cross-flight double-coverage, the blue areas that are not covered by both a horizontal and a vertical swath are considered data voids, which are grounds for rejection of the project.

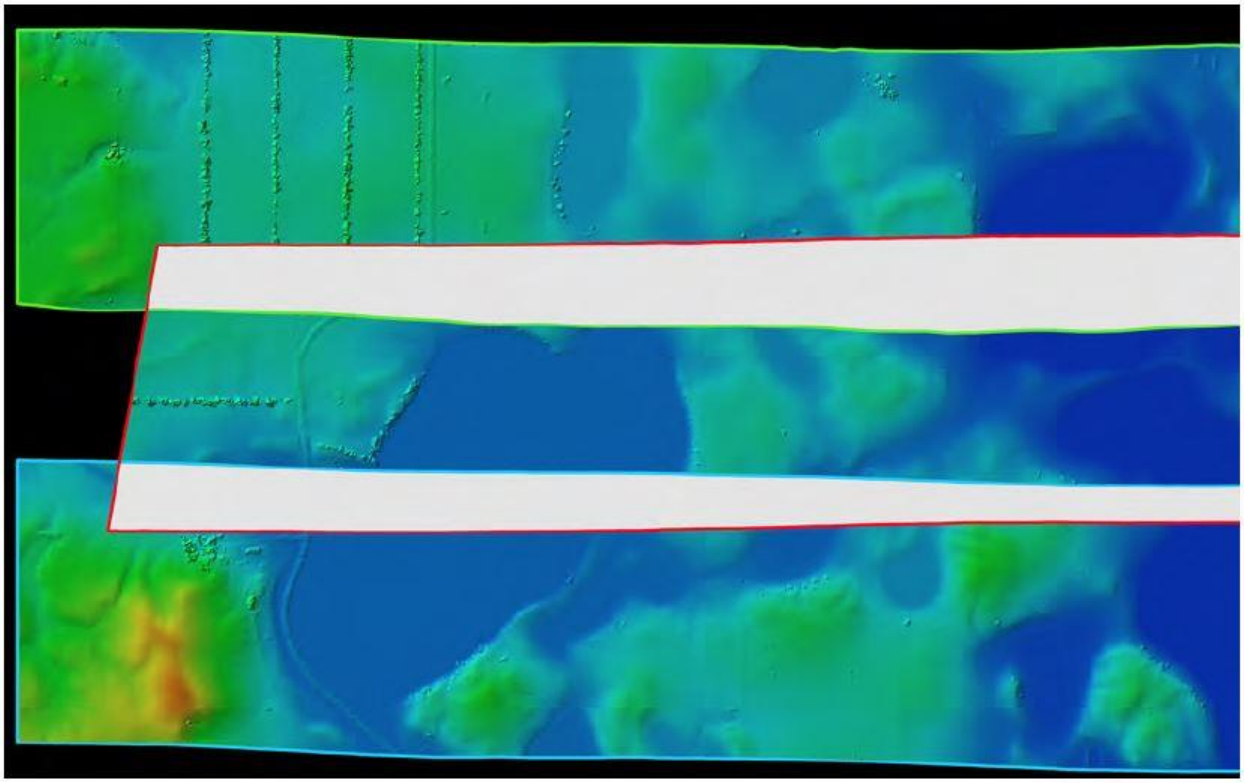

Figure 4. Graphic depiction of swath overlap. Three light detection and ranging swaths are depicted with the edges colored blue, red, and green. Each adjacent pair of swaths shares one overlap region shown in gray.

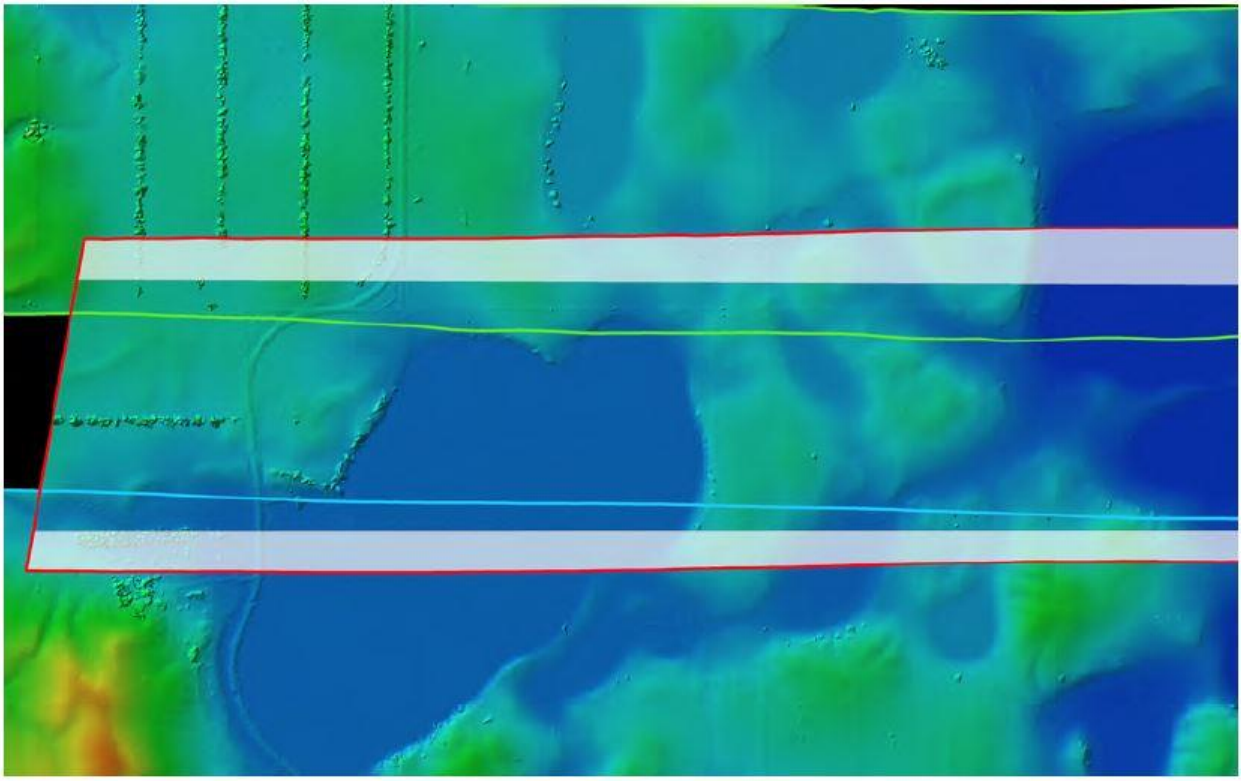

Figure 5. Graphic depiction of swath overage. Three light detection and ranging swaths are depicted with the edges colored blue, red, and green. Each individual swath has an overage region shown in gray for each adjacent, overlapping swath.

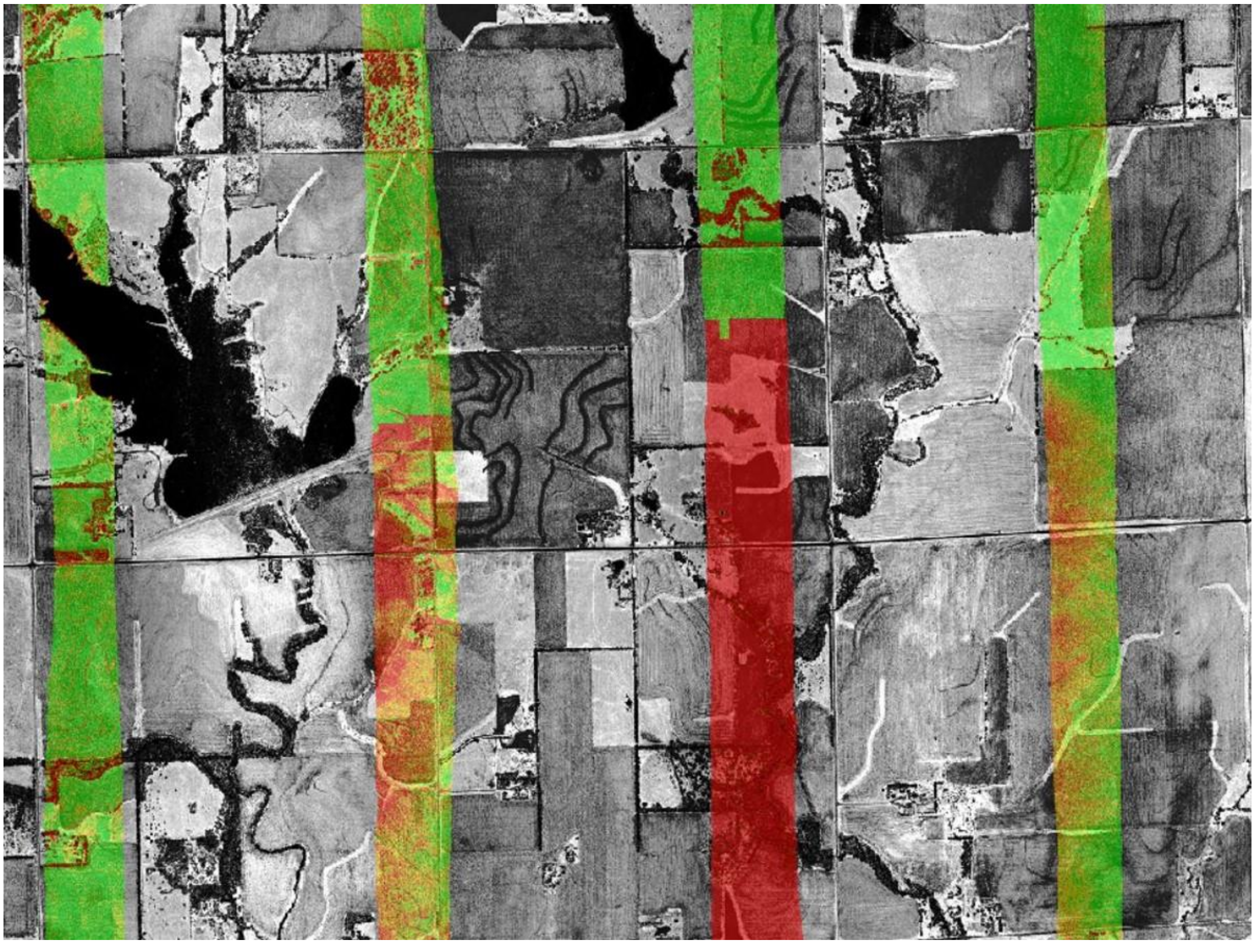

Figure 6: Example of a Swath Separation Image. Overlapping swath differences were calculated using a TIN algorithm. Point-in-pixel algorithm also okay as long as the spatial resolution is coarse enough to contain at least one point from each swath. Pixel colors are based on swath differences using green for 0 cm to 8 cm, yellow for 8 cm to 16 cm, and red for greater than 16 cm. Continuous RGB values throughout area of overlap make it possible to see patterns in the data. A distinct vertical offset in this dataset is indicated by red pixels in the most central overlap region.

Glossary

Note: Many of the following definitions are from Maune (2007) and American Society for Photogrammetry and Remote Sensing (ASPRS) (2014) and are used with permission.

A

accuracy The closeness of an estimated value (for example, measured or computed) to a standard or accepted (true) value of a particular quantity. *See* **precision**.

- **accuracy, absolute** A measure that accounts for all systematic and random errors in a dataset. Absolute accuracy is stated with respect to a defined datum or reference system.
- **accuracy$_r$ (ACC$_r$)** The National Standards for Spatial Data Accuracy (NSSDA) (Federal Geographic Data Committee, 1998) reporting standard in the horizontal component that equals the radius of a circle of uncertainty, such that the true or theoretical horizontal location of the point falls within that circle 95 percent of the time.

  $$ACC_r = 1.7308 * RMSE_r$$

  See **RMSE$_r$**.
- **accuracy$_z$ (ACC$_z$)** The NSSDA reporting standard in the vertical component that equals the linear uncertainty value, such that the true or theoretical vertical location of the point falls within that linear uncertainty value 95 percent of the time.

  $$ACC_z = 1.9600 * RMSE_z$$

  See **RMSE$_z$**.
- **accuracy, horizontal** The horizontal (radial) component of the positional accuracy of a dataset with respect to a horizontal datum, at a specified confidence level. *See* **accuracy$_r$**.
- **accuracy, local** The uncertainty in the coordinates of points with respect to coordinates of other directly connected, adjacent points at the 95-percent confidence level.
- **accuracy, network** The uncertainty in the coordinates of mapped points with respect to the geodetic datum at the 95-percent confidence level.
- **accuracy, positional** The accuracy at the 95-percent confidence level of the position of features, including horizontal and vertical positions, with respect to horizontal and vertical datums.
- **accuracy, relative** A measure of variation in point-to-point accuracy in a dataset. In light detection and ranging (lidar), this term may also specifically mean the positional agreement between points within a swath, adjacent swaths within a lift, adjacent lifts within a project, or between adjacent projects.
- **accuracy, vertical** The measure of the positional accuracy of a dataset with respect to a specified vertical datum at a specified confidence level or percentile. *See* **accuracy$_z$**.

aggregate nominal pulse density (ANPD) A variant of nominal pulse density that expresses the total expected or actual density of pulses located in a specified unit area resulting from multiple passes of the lidar instrument, or a single pass of a platform with multiple lidar instruments, over the same target area. In all other respects, ANPD is identical to nominal pulse density (NPD). In single coverage collection, ANPD and NPD will be equal. *See* **aggregate nominal pulse spacing**, **nominal pulse density**, **nominal pulse spacing**.

aggregate nominal pulse spacing (ANPS) A variant of nominal pulse spacing that expresses the typical or average lateral distance between pulses in a lidar dataset resulting from multiple passes of the lidar instrument, or a single pass of a platform with multiple lidar instruments, over the same target area. In all other respects, ANPS is identical to nominal pulse spacing (NPS). In single coverage collections, ANPS and NPS will be equal. *See* **aggregate nominal pulse density**, **nominal pulse density**, **nominal pulse spacing**.

aqueduct A structure designed to transport domestic or industrial water from a supply source to a distribution point, often by gravity.

artifacts An inaccurate observation, effect, or result, especially one resulting from the technology used in scientific investigation or from experimental error. In bare-earth elevation models, artifacts are detectable surface remnants of buildings, trees, towers, telephone poles, or other elevated features; also, detectable artificial anomalies that are introduced to a surface model by way of system specific collection or processing techniques. For example, corn-row effects of profile collection, star and ramp effects from multidirectional contour interpolation, or detectable triangular facets caused when vegetation canopies are removed from lidar data.

attitude The position of a body defined by the angles between the axes of the coordinate system of the body and the axes of an external coordinate system. In photogrammetry, the attitude is the angular orientation of a camera (roll, pitch, yaw), or of the photograph taken with that camera, with respect to some external reference system. With lidar, the attitude is normally defined as the roll, pitch, and heading of the instrument at the instant an active pulse is emitted from the sensor.

B

bald earth Nonpreferred term. *See* **bare-earth**.

bare-earth (bare earth) Digital elevation data of the terrain free from vegetation, buildings, and other man-made structures. Elevations of the ground.

blunder A mistake resulting from carelessness or negligence.

boresight Calibration of a lidar sensor system equipped with an Inertial Measurement Unit (IMU) and Global Positioning System (GPS) to determine or establish the accurate position of the instrument (*x, y, z*) with respect to the GPS antenna and orientation (roll, pitch, heading) of the lidar instrument with respect to straight and level flight.

breakline A linear feature that describes a change in the smoothness or continuity of a surface. The two most common forms of breaklines are as follows:

- **breakline, soft** Ensures that known *z*-values along a linear feature are maintained (for example, elevations along a pipeline, road centerline, or drainage ditch), and ensures that linear features and polygon edges are maintained in a triangulated irregular network (TIN) surface model by enforcing the breaklines as TIN edges. They are generally synonymous with 3-dimensional (3D) breaklines because they are depicted with series of *x, y, z* coordinates. Somewhat rounded ridges or the trough of a drain may be collected using soft breaklines.
- **breakline, hard** Defines interruptions in surface smoothness (for example, to define streams, rivers, shorelines, dams, ridges, building footprints, and other locations) with abrupt surface changes. Although some hard breaklines are 3D breaklines, they are typically depicted as 2-dimensional (2D) breaklines because features such as shorelines and building footprints are

normally depicted with series of *x*, *y* coordinates only, which are often digitized from digital orthophotos that include no elevation data.

See **mass point**.

bridge A structure carrying a road, path, railroad, canal, aircraft taxiway, or any other transit between two locations of higher elevation over an area of lower elevation. A bridge may traverse a river, ravine, road, railroad, or other obstacle. “Bridge” also includes but is not limited to aqueduct, drawbridge, flyover, footbridge, overpass, span, trestle, and viaduct. In mapping, the term “bridge” is distinguished from a roadway over a culvert in that a bridge is an elevated deck that is not underlain with earth or soil. *See* **culvert, saddle**.

- **calibration (lidar systems)** The process of identifying and correcting for systematic errors in hardware, software, or data. Determining the systematic errors in a measuring device by comparing its measurements with the markings or measurements of a device that is considered correct. Lidar system calibration falls into two main categories:
- **calibration, instrument** Factory calibration includes radiometric and geometric calibration unique to each manufacturer’s hardware and tuned to meet the performance specifications for the model being calibrated. Instrument calibration can only be assessed and corrected by the instrument manufacturer.
- **calibration, data** The lever arm calibration determines the sensor-to-GPS-antenna offset vector (the lever arm) components relative to the antenna phase center. The offset vector components are redetermined each time the sensor or aircraft GPS antenna are moved or repositioned. Because normal aircraft operations can induce slight variations in component mounting, the components are normally field calibrated for each project, or even daily, to determine corrections to the roll, pitch, yaw, and scale calibration parameters.

C

calibration point Nonpreferred term. *See* **control point**.

cell (pixel) A single element of a raster dataset. Each cell contains a single numeric value of information representative of the area covered by the cell. Although the terms “cell” and “pixel” are synonymous, in this specification “cell” is used in reference to nonimage rasters such as digital elevation models (DEMs), whereas “pixel” is used in reference to image rasters such as lidar intensity images.

check point (checkpoint) A surveyed point (*x, y* or *x, y, z*) used to estimate the positional accuracy of a geospatial dataset against an independent source of greater accuracy. Check points are independent from, and may never be used as, control points on the same project.

classification (of lidar) The classification of lidar point cloud returns in accordance with a classification scheme to identify the type of target from which each lidar return is reflected. The process allows future differentiation between bare-earth terrain points, water, noise, vegetation, buildings, other man-made features, and objects of interest.

confidence level The percentage of points within a dataset that are estimated to meet the stated accuracy; for example, accuracy reported at the 95-percent confidence level means that 95 percent of the positions in the dataset will have an error with respect to true ground position that are equal to or smaller than the reported accuracy value.

consolidated vertical accuracy (CVA) Replaced by the term vegetated vertical accuracy (VVA) in this specification, CVA is the term used by the National Digital Elevation Program (NDEP) guidelines for vertical accuracy at the 95th percentile in all land cover categories combined (NDEP, 2004). *See* **percentile**, **vegetated vertical accuracy**.

control point (calibration point) A surveyed point used to geometrically adjust a lidar dataset to establish its positional accuracy relative to the real world. Control points are independent from, and may never be used as, check points on the same project.

CONUS Continental United States, the conterminous 48 States.

culvert A tunnel carrying a stream or open drainage under a road or railroad or through another type of obstruction to natural drainage. Typically constructed of formed concrete or corrugated metal and surrounded on all sides, top, and bottom by earth or soil.

D

data void In lidar, a gap in the point cloud coverage caused by surface nonreflectance of the lidar pulse, instrument or processing anomalies or failure, obstruction of the lidar pulse, or improper collection flight planning. Any area greater than or equal to four times the ANPS, squared, measured using first returns only, is considered to be a data void.

datum A set of reference points on the Earth's surface against which position measurements are made, and (usually) an associated model of the shape of the Earth (reference ellipsoid) to define a geographic coordinate system. Horizontal datums (for example, the North American Datum of 1983 [NAD 83]) are used for describing a point on the Earth's surface, in latitude and longitude or another coordinate system. Vertical datums (for example, the North American Vertical Datum of 1988 [NAVD 88]) are used to measure elevations or depths. In engineering and drafting, a datum is a reference point, surface, or axis on an object against which measurements are made.

digital elevation model resolution The linear size of each cell of a raster DEM. Features smaller than the cell size cannot be explicitly represented in a raster model. DEM resolution may also be referred to as cell size, grid spacing, or ground sample distance.

digital elevation model (DEM) *See* four different definitions below:

- A popular acronym used as a generic term for digital topographic and bathymetric data in all its various forms. Unless specifically referenced as a digital surface model (DSM), the generic DEM normally implies *x*, *y* coordinates and *z*-values of the bare-earth terrain void of vegetation and man-made features.
- As used by the U.S. Geological Survey (USGS), a DEM is the digital cartographic representation of the elevation of the land at regularly spaced intervals in *x* and *y* directions, using *z*-values referenced to a common vertical datum.
- As typically used in the United States and elsewhere, a DEM has bare-earth *z*-values at regularly spaced intervals in *x* and *y* directions; however, grid spacing, datum, coordinate systems, data formats, and other characteristics may vary widely.
- A “D-E-M” is a specific raster data format once widely used by the USGS. DEMs are a sampled array of elevations for a number of ground positions at regularly spaced intervals.

digital surface model (DSM) Similar to DEMs except that they may depict the elevations of the top surfaces of buildings, trees, towers, and other features elevated above the bare-earth. DSMs are especially relevant for telecommunications management, air safety, forest management, and 3D modeling and simulation.

digital terrain model (DTM) *See* two different definitions below:

- In some countries, DTMs are synonymous with DEMs, representing the bare-earth terrain with uniformly spaced *z*-values, as in a raster.
- As used in the United States, a "DTM" is a vector dataset composed of 3D breaklines and regularly spaced 3D mass points, typically created through stereo photogrammetry, that characterize the shape of the bare-earth terrain. Breaklines more precisely delineate linear features whose shape and location would otherwise be lost. A DTM is not a surface model and its component elements are discrete and not continuous; a TIN or DEM surface must be derived from the DTM. Surfaces derived from DTMs can represent distinctive terrain features much better than those generated solely from gridded elevation measurements. A lidar point dataset combined with ancillary breaklines is also considered a DTM.

discrete return lidar Lidar system or data in which important peaks in the waveform are captured and stored. Each peak represents a return from a different target, discernible in vertical or horizontal domains. Most modern lidar systems are capable of capturing multiple discrete returns from each emitted laser pulse. *See* **waveform lidar**.

E

elevation The distance measured upward along a plumb line between a point and the geoid. The elevation of a point is normally the same as its orthometric height, defined as H in the equation:

$$H=h-N,$$

where:

h is equal to the ellipsoid height and

N is equal to the geoid height.

F

first return (first-return) The first important measurable part of a return lidar pulse.

flightline A single pass of the collection aircraft over the target area. Commonly used incorrectly to refer to the data resulting from a flightline of collection. *See* **swath**.

fundamental vertical accuracy (FVA) Replaced by the term nonvegetated vertical accuracy (NVA), in this specification, FVA is the term used by the National Digital Elevation Program (NDEP) guidelines for vertical accuracy at the 95-percent confidence level in open terrain only where errors should approximate a normal error distribution. *See* **nonvegetated vertical accuracy**, **accuracy**, **confidence level**.

G

geographic information system (GIS) A system of spatially referenced information, including computer programs that acquire, store, manipulate, analyze, and display spatial data.

geospatial data Information that identifies the geographic location and characteristics of natural or constructed features and boundaries of earth. This information may be derived from—among other things—remote-sensing, mapping, and surveying technologies. Geospatial data generally are considered to be synonymous with spatial data; however, the former always is associated with geographic or Cartesian coordinates linked to a horizontal or vertical datum, whereas the latter (for example, generic architectural house plans) may include dimensions and other spatial data not linked to any physical location.

ground truth Verification of a situation without errors introduced by sensors or human perception and judgment.

H

hillshade A function used to create an illuminated representation of the surface, using a hypothetical light source, to enhance terrain visualization effects.

horizontal accuracy Positional accuracy of a dataset with respect to a horizontal datum. According to the National Standards for Spatial Data Accuracy (NSSDA), horizontal (radial) accuracy at the 95-percent confidence level is defined as ACCr. *See* a**Accuracy, horizontal**.

hydraulic modeling The use of digital elevation data, rainfall-runoff data from hydrologic models, surface roughness data, and information on hydraulic structures (for example, bridges, culverts, dams, weirs, and sewers) to predict flood levels and manage water resources. Hydraulic models are based on computations involving liquids under pressure, and many other definitions of hydraulic modeling exist that are not associated with terrain elevations (for example, modeling of hydraulic lines in aircraft and automobiles).

hydrologic modeling The computer modeling of rainfall and the effects of land cover, soil conditions, and terrain slope to estimate rainfall runoff into streams, rivers, and lakes. Digital elevation data are used as part of hydrologic modeling.

hydrologically conditioned (hydro-conditioned) Processing of a DEM or TIN so that the flow of water is continuous across the entire terrain surface, including the removal of all isolated sinks or pits. The only sinks that are retained are the real ones on the landscape. Although hydrologically enforced is relevant to drainage features that generally are mapped, hydrologically conditioned is relevant to the entire land surface and is done so that water flow is continuous across the surface, whether that flow is in a stream channel or not. The purpose for continuous flow is so that relations and (or) links among basins and (or) catchments can be known for large areas.

hydrologically flattened (hydro-flattened) Processing of a lidar-derived surface (DEM or TIN) so that mapped waterbodies, streams, rivers, reservoirs, and other cartographically polygonal water surfaces are flat and, where appropriate, level from bank to bank. Additionally, surfaces of streams, rivers, and long reservoirs demonstrate a gradient change in elevation along their length, which is consistent with their natural behavior and the surrounding topography. In traditional maps that are compiled photogrammetrically, this process is accomplished automatically through the inclusion of measured breaklines in the DTM; however, because lidar does not inherently include breaklines, a DEM or TIN derived solely from lidar points will depict water surfaces with unsightly and unnatural artifacts of triangulation. The process of hydro-flattening typically involves the addition of breaklines along the banks of specified waterbodies, streams, rivers, and ponds. These breaklines establish elevations for the water surfaces that are consistent with the surrounding topography and produce aesthetically acceptable water surfaces in the final DEM or TIN. Unlike hydro-conditioning and hydro-enforcement, hydro-flattening is not driven by any hydrologic and hydraulic (H&H) modeling requirements but solely by cartographic mapping needs.

hydrologically enforced (hydro-enforced) Processing of mapped waterbodies so that lakes and reservoirs are level and so that streams and rivers flow downhill; for example, a DEM, TIN, or topographic contour dataset with elevations removed from the tops of selected drainage structures (bridges and culverts) so as to depict the terrain under those structures. Hydro-enforcement enables hydrologic and hydraulic models to depict water flowing under these structures, rather than appearing in the computer model to be dammed by them because of road deck elevations higher than the water levels. Hydro-enforced TINs also use breaklines along shorelines and stream centerlines (for example, where these breaklines form the edges of TIN triangles along the alignment of drainage features). Shore breaklines for streams and rivers would be 3D breaklines with elevations that decrease as the stream flows downstream; however, shore breaklines for lakes or reservoirs would have the same elevation for the entire shoreline if the water surface is known or assumed to be level throughout.

I

intensity (lidar) For discrete-return lidar instruments, intensity is the recorded amplitude of the reflected lidar pulse at the moment the reflection is captured as a return by the lidar instrument. Lidar intensity values can be affected by many factors such as the instantaneous setting of the instrument’s Automatic Gain Control and angle of incidence and thus cannot be equated to a true measure of energy for discrete return systems. In full-waveform systems, the entire reflection is sampled and recorded, and true energy measurements can be made for each return or overall reflection. Intensity values for discrete returns derived from a full-waveform system may or may not be calibrated to represent true energy. Lidar intensity data make it possible to map variable textures in the form of a grayscale image. Intensity return data enable automatic identification and extraction of objects such as buildings and impervious surfaces and can aid in lidar point classification. In spite of their similar appearance, lidar intensity images differ from traditional panchromatic images in several important ways:

- Lidar intensity is a measure of the reflection of an active laser energy source, not natural solar energy.
- Lidar intensity images are aggregations of values at point samples. The value of a pixel does not represent the composite value for the area of that pixel.
- Lidar intensity images depict the surface reflectivity within an extremely narrow band of the electromagnetic spectrum, not the entire visible spectrum as in panchromatic images.
- Lidar intensity images are strongly affected by the angle of incidence of the laser to the target and are subject to unnatural shadowing artifacts.
- The values on which lidar intensity images are based may or may not be calibrated to any standard reference. Intensity images usually contain wide variation of values within swaths, between swaths, and between lifts.

For these reasons, lidar intensity images must be interpreted and analyzed with unusually high care and skill.

L

LAS A public file format for the interchange of 3D point cloud data between data users. The file extension is .las. (ASPRS, 2011)

last return The last important measurable part of a return lidar pulse.

lattice A 3D vector representation method created by a rectangular array of points spaced at a constant sampling interval in *x* and *y* directions relative to a common origin. A lattice differs from a grid in that it represents the value of the surface only at the lattice mesh points rather than the elevation of the cell area surrounding the centroid of a grid cell.

lever arm A relative position vector of one sensor with respect to another in a direct georeferencing system. For example, with aerial mapping cameras, lever arms are positioned between the inertial center of the Inertial Measurement Unit (IMU) and the phase center of the Global Positioning System (GPS) antenna, each with respect to the camera perspective center within the lens of the camera.

lidar An instrument that measures distance to a reflecting object by emitting timed pulses of light and measuring the time difference between the emission of a laser pulse and the reception of the pulse's reflection(s). The measured time interval for each reflection is converted to distance, which when combined with position and attitude information from GPS, IMU, and the instrument itself, allows the derivation of the 3D point location of the reflecting target's location.

lidar systems *See* **calibration**.

lift A lift is a single takeoff and landing cycle for a collection platform (fixed or rotary wing) within an aerial data collection project, often lidar.

Mlocal accuracy *See a***Accuracy, local**.

mass point(s) Irregularly spaced points, each with *x, y, z* coordinates, typically (but not always) used to form a TIN. When generated manually, mass points are ideally chosen to depict the most significant variations in the slope or aspect of TIN triangles; however, when generated automatically (for example, by lidar), mass point spacing and pattern depend upon the characteristics of the technologies used to acquire the data. Mass points are usually used in conjunction with breaklines. *See* **breakline**.

metadata Any information that is descriptive or supportive of a geospatial dataset, including formally structured and formatted metadata files (for example, eXtensible Markup Language [XML]-formatted Federal Geographic Data Committee [FGDC] metadata), reports (collection, processing, quality assurance/quality control [QA/QC]), and other supporting data (for example, survey points, shapefiles).

monotonic In mathematics, a function that varies such that it either increases or decreases, but never both. As used in this specification, it describes a hydrographic breakline that continuously flows either level or downhill, but never uphill.

N

nominal pulse density (NPD) A common measure of the density of a lidar dataset; NPD is the typical or average number of pulses within a specified areal unit. NPD is typically expressed as pulses per square meter. This value is predicted in mission planning and empirically calculated from the collected data, using only the first (or last) return points as surrogates for pulses. As used in this specification, NPD refers to single swath, single instrument data, whereas ANPD describes the overall pulse density resulting from multiple passes of the lidar instrument, or a single pass of a platform with multiple lidar instruments, over the same target area. NPD is more commonly used in high-density collections (greater than or equal to 1 pulses per square meter [pls/m2]), with its inverse, NPS, being used in low-density collections (less than or equal to 1 pls/m2). Assuming meters are being used in both expressions, NPD can be calculated from NPS using the formula *NPD* = 1/*NPS* 2. *See* **aggregate nominal pulse density**, **aggregate nominal pulse spacing**, **nominal pulse spacing**.

nominal pulse spacing (NPS) A common measure of the density of a lidar dataset, NPS is the typical or average lateral distance between pulses in a lidar dataset, typically expressed in meters and most simply calculated as the square root of the average area per first return point. This value is predicted in mission planning and empirically calculated from the collected data, using only the first (or last) return points as surrogates for pulses. As used in this specification, NPS refers to single swath, single instrument data, whereas ANPS describes the overall pulse spacing resulting from multiple passes of the lidar instrument, or a single pass of a platform with multiple lidar instruments, over the same target area. NPS is more commonly used in low-density collections (greater than or equal to 1 m NPS), with its inverse, NPD, being used in high-density collections (less than 1 m NPS). Assuming meters are being used in both expressions, NPS can be calculated from NPD using the formula *NPS* = 1/√*NPD*. *See* **aggregate nominal pulse density**, **aggregate nominal pulse spacing**, **nominal pulse density**.

nonvegetated vertical accuracy (NVA) Replaces fundamental vertical accuracy (FVA). The vertical accuracy at the 95-percent confidence level in nonvegetated open terrain, where errors should approximate a normal distribution. *See* **fundamental vertical accuracy**.

O

overage Those parts of a swath that are not necessary to form a complete single, nonoverlapped, gap-free coverage with respect to the adjacent swaths. The nontenderloin parts of a swath. In collections designed using multiple coverage, overage are the parts of the swath that are not necessary to form a complete nonoverlapped coverage at the planned depth of coverage. In LAS specification version 1.4–R15 (ASPRS, 2011), these points are identified by using the incorrectly named “overlap” bit flag. *See* **overlap**, **tenderloin**.

overlap Any part of a swath that also is covered by any part of any other swath. The term overlap is incorrectly used in LAS specification version 1.4–R15 (ASPRS, 2011) to describe the bit flag intended to identify overage points. *See* **overage**, **tenderloin**.

P

penstock A structure designed to convey water into the turbine of a hydro-electric generating plant. Typically the main pipes within a large hydro-electric dam.

percentile A measure used in statistics indicating the value below which a given percentage of observations (absolute values of errors) in a group of observations fall. For example, the 95th percentile is the value (or score) below which 95 percent of the observations may be found. There are different approaches to determining percentile ranks and associated values. This specification recommends the use of the following equations for computing percentile rank and percentile as the most appropriate for estimating the vegetated vertical accuracy (VVA). Note that percentile calculations are based on the absolute values of the errors because it is the magnitude of the errors, not the sign, which is of concern. The percentile rank (*n*) is first calculated for the desired percentile using the following equation:

$$n = \left(\left(\frac{P}{100}\right) * (N - 1)\right) + 1$$

where:

n	is the rank of the observation that contains the *Pth* percentile,
P	is the proportion (of 100) at which the percentile is desired (for example, 95 for 95th percentile), and
N	is the number of observations in the sample dataset.

Once the rank of the observation is determined, the percentile (*Qp*) can then be interpolated from the upper and lower observations using the following equation:

$$\boldsymbol{Q_p} = (\boldsymbol{A}[\boldsymbol{n_w}] + (\boldsymbol{n_d} * (\boldsymbol{A}[\boldsymbol{n_w} + \mathbf{1}] - \boldsymbol{A}[\boldsymbol{n_w}])))$$

where:

$\boldsymbol{Q_p}$	is the *Pth* percentile; the value at ran *n*;
$\boldsymbol{A}$	is the array of the absolute values of the samples, indexed in ascending order from 1 to *N*;
$\boldsymbol{A}[\boldsymbol{n_w}]$	is the sample value of array *A* at index *i* (for example, *nw* or *nd*). *i* must be an integer between 1 and *N*;
$\boldsymbol{n}$	is the rank of the observation that contains the *Pth* percentile;
$\boldsymbol{n_w}$	is the whole number component of *n* (for example, 3 of 3.14); and
$\boldsymbol{n_d}$	is the decimal component of *n* (for example, 0.14 of 3.14).

pixel *See* **cell**.

playa An undrained desert basin that periodically fills with water to form a temporary lake. Playas drain directly into the ground. They can often be identified by having apparent inlet channels but no outlets, and with flat and level floors.

point classification The assignment of a target identity classification to a particular lidar point or group of points.

point cloud One of the fundamental types of geospatial data (others being vector and raster), a point cloud is a large set of 3D points, typically from a lidar collection. As a basic geographic information system (GIS) data type, a point cloud is differentiated from a typical point dataset in several key ways:

- point clouds are almost always 3D,
- point clouds have an order of magnitude more features than point datasets, and

- individual point features in point clouds do not typically possess individually meaningful attributes; the informational value in a point cloud is derived from the relations among large numbers of features. See raster, vector.

See **raster**, **vector**

precision (repeatability) The closeness with which measurements agree with each other, even though they may all contain a systematic bias. *See* **accuracy**.

point family The complete set of multiple returns reflected from a single lidar pulse.

preprocessing In lidar, the preprocessing of data most commonly refers to those steps used in converting the collected GPS, IMU, instrument, and ranging information into an interpretable *X-Y-Z* point cloud, including generation of trajectory information, calibration of the dataset, and controlling the dataset to known ground references.

postprocessing In lidar, postprocessing refers to the processing steps applied to lidar data point clouds, including point classification, feature extraction (for example, building footprints, hydrographic features, and others), tiling, and generation of derivative products (DEMs, DSMs, intensity images, and others).

R

raster One of the fundamental types of geospatial data (others being vector and point cloud), a raster is an array of cells (or pixels) that each contain a single piece of numeric information representative of the area covered by the cell. Raster datasets are spatially continuous; with respect to DEMs, this quality creates a surface from which information can be extracted from any location. As spatial arrays, rasters are always rectangular; cells are most often square. Co-located rasters can be stored in a single file as layers, as with color digital images. *See* **raster**, **vector**.

repeatability *See* **precision**.

resolution The smallest unit a sensor can detect or the smallest unit a raster DEM depicts. The degree of fineness to which a measurement can be made. "Resolution" is also used to describe the linear size of an image pixel or raster cell.

root mean square difference (RMSD) The square root of the average of the set of squared differences between two dataset coordinate values taken at identical locations. RMSD differentiates from root mean square error (RMSE) because neither dataset is known to be more or less accurate than the other, and the differences cannot be regarded as errors. RMSD is used in lidar when assessing relative accuracy, both intraswath and interswath. *See* **root mean square error**.

root mean square error (RMSE) The square root of the average of the set of squared differences between dataset coordinate values and coordinate values from an independent source of higher accuracy for identical points. The RMSE is used to estimate the absolute accuracy of both horizontal and vertical coordinates when standard or accepted values are known, as with GPS-surveyed check points of higher accuracy than the data being tested. In the United States, the independent source of higher accuracy is expected to be at least three times more accurate than the dataset being tested.

RMSE$_r$ The horizontal root mean square error in the radial direction that includes both *x* and *y* coordinate errors.

$$\sqrt{(RMSE_x^2 + RMSE_y^2)}$$

where:

$RMSE_x$ is the RMSE in the *x* direction, and

$RMSE_y$ is the RMSE in the *y* direction.

- **RMSE$_x$** The horizontal root mean square error in the *x* direction (easting).

$$\sqrt{\sum \frac{(\boldsymbol{x_n} - \boldsymbol{x'_n})^2}{\boldsymbol{N}}}$$

where:

$\boldsymbol{x_n}$ is the set of $\boldsymbol{N}$ $\boldsymbol{x}$ coordinates being evaluated,

$\boldsymbol{x'_n}$ is the corresponding set of check point *x* coordinates for the points being evaluated,

$\boldsymbol{N}$ is the number of *x* coordinate check points, and

$\boldsymbol{n}$ is the identification number of each check point from 1 through $\boldsymbol{N}$.

- **RMSE$_y$** The horizontal root mean square error in the *y* direction (northing).

$$\sqrt{\sum \frac{(\boldsymbol{y_n} - \boldsymbol{y'_n})^2}{\boldsymbol{N}}}$$

where:

$\boldsymbol{y_n}$ is the set of $\boldsymbol{N}$ $\boldsymbol{y}$ coordinates being evaluated,

$\boldsymbol{y'_n}$ is the corresponding set of check point *y* coordinates for the points being evaluated,

$\boldsymbol{N}$ is the number of *y* coordinate check points, and

$\boldsymbol{n}$ is the identification number of each check point from 1 through $\boldsymbol{N}$.

- **RMSE$_z$** The vertical root mean square error in the *z* direction (elevation).

$$\sqrt{\sum \frac{(\boldsymbol{z_n} - \boldsymbol{z'_n})^2}{\boldsymbol{N}}}$$

where:

$\boldsymbol{z_n}$ is the set of $\boldsymbol{N}$ $\boldsymbol{z}$ values (elevations) being evaluated,

$\boldsymbol{z'_n}$ is the corresponding set of check point elevations for the points being evaluated,

$\boldsymbol{N}$ is the number of *z* coordinate check points, and

$\boldsymbol{n}$ is the identification number of each check point from 1 through $\boldsymbol{N}$.

S

saddle The lowest area between two opposing higher terrain features, usually connecting two areas of lower terrain, as in a mountain pass. Used in this specification to reference the area exposed by the removal or exclusion of a bridge deck from a DEM. *See* **bridge**.

siphon A structure designed to convey water by gravitational force over, or under, an obstruction. Often seen as vertical pipes in smaller ponds with earthen dams that convey overflow water under the dam.

spatial distribution In lidar, the regularity or consistency of the point density within the collection. The theoretical ideal spatial distribution for a lidar collection is a perfect regular lattice of points with equal spacing on x and y axes. Various factors prevent this ideal from being achieved, including the following factors:

- instrument design (oscillating mirrors),
- mission planning (difference between along-track and cross-track pulse spacing), and
- in-flight attitude variations (roll, pitch, and yaw).

standard deviation A measure of spread or dispersion of a sample of errors around the sample mean error. It is a measure of precision, rather than accuracy; the standard deviation does not account for uncorrected systematic errors.

supplemental vertical accuracy (SVA) Merged into the Vegetated Vertical Accuracy (VVA) in this specification, SVA is the NDEP guidelines term for reporting the vertical accuracy at the 95th percentile in each separate land cover category where vertical errors may not follow a normal error distribution. *See* **percentile**, **vegetated vertical accuracy**.

swath The data resulting from a single flightline of collection. Swaths can be considered as one of five general types:

- **project** Originally planned to cover the project area.
- **cross-tie** Originally planned and within the project area, but intended for calibration/boresighting purposes only.
- **calibration** Data collected for calibration/boresighting purposes only, usually over the base airport, and often not within the project area.
- **fill-in** Additional swaths collected to fill unplanned gaps or areas of low data density discovered in the planned project area collection.
- **other** Any swath that does not meet the above definitions.

See **flightline**.

systematic error An error whose algebraic sign and, to some extent, magnitude bears a fixed relation to some condition or set of conditions. Systematic errors follow some fixed pattern and are introduced by data collection procedures, processing, or given datum.

T

tenderloin The central part of the swath that, when combined with adjacent swath tenderloins, forms a complete, single, nonoverlapped, gap-free coverage. In collections designed using multiple coverage, tenderloins are the parts of the swath necessary to form a complete nonoverlapped, gap-free coverage at the planned depth of coverage. *See* **overage**, **overlap**.

topology The spatial relationship between geographic features in a common space. Examples particularly relevant to this specification include precise coincidence of ending and beginning vertices of lines in a continuous network (stream connectivity), and consistent line direction (from high to low) corresponding to streamflow direction.

triangulated irregular network (TIN) A vector data structure that partitions geographic space into contiguous, nonoverlapping triangles. In lidar, the vertices of each triangle are lidar points with *x*, *y*, and *z* values. In most geographic applications, TINs are based on Delaunay triangulation algorithms in which no point in any given triangle lies within the circumcircle of any other triangle.

U

uncertainty (of measurement) A parameter that characterizes the dispersion of measured values, or the range in which the "true" value most likely lies. It can also be defined as an estimate of the limits of the error in a measurement (where "error" is defined as the difference between the theoretically unknowable "true" value of a parameter and its measured value). Standard uncertainty refers to uncertainty expressed as a standard deviation.

V

vector One of the fundamental types of geospatial data (others being raster and point cloud), vectors include a variety of data structures that are geometrically described by *x*, *y*, and potentially *z* coordinates. Vector data subtypes include points, lines, and polygons. A DTM consisting of mass points and breaklines is an example of a vector dataset; a TIN is a vector surface. *See* **point cloud**, **raster**.

vegetated vertical accuracy (VVA) Replaces supplemental vertical accuracy (SVA) and CVA. An estimate of the vertical accuracy, based on the 95th percentile, in vegetated terrain where errors do not necessarily approximate a normal distribution. *See* **percentile**, **nonvegetated vertical accuracy**.

W

waveform lidar Lidar system or data in which the entire reflection of the laser pulse is fully digitized, captured, and stored. Discrete return point clouds can be extracted from the waveform data during postprocessing. *See* **Discrete Return Lidar**.

well-distributed For a dataset covering a rectangular area that has uniform positional accuracy, check points should be distributed so that points are spaced at intervals of at least 10 percent of the diagonal distance across the dataset and at least 20 percent of the points are located in each quadrant of the dataset (adapted from the National Standards for Spatial Data Accuracy of the Federal Geographic Data Committee, 1998). As related to this specification, these guidelines are applicable to each land cover class for which check points are being collected.

withheld Within the LAS file specification, a single bit flag indicating that the associated lidar point is geometrically anomalous or unreliable and should be ignored for all normal processes. These points are retained because of their value in specialized analysis. Withheld points typically are identified and tagged during preprocessing or through the use of automatic classification routines. Examples of points typically tagged as withheld are listed below:

- spatial outliers in either the horizontal or vertical domains, and
- geometrically unreliable points near the edge of a swath.

Appendix 1

A partial list of common upgrades, which is neither comprehensive nor exclusive.

- Independent third-party quality assurance/quality control by another contractor.
- Full Waveform collection and delivery.
- Additional Environmental Constraints.
  - Tidal coordination, flood stages, crop or plant growth cycles.
  - Shorelines corrected for tidal variations within a collection.
- Top-of-Canopy (First Return) Raster Surface (tiled).
  - Raster representing the highest return within each cell is preferred.
- Intensity Images (8-bit grayscale, tiled).
  - Interpolation based on First Returns.
  - Interpolation based on All-Returns, summed.
- Detailed Classification (additional classes).
  - Class 3: Low vegetation.
  - Class 4: Medium Vegetation (use for single vegetation class).
  - Class 5: High Vegetation.
  - Class 6: Buildings, other man-made structures.
  - Class n: Additional classes or features as agreed upon in advance.
- Hydro-enforced digital elevation models (DEMs) as an additional deliverable.
- Hydro-conditioned DEMs as an additional deliverable.
- Breaklines (PolylineZ and PolygonZ) for additional hydrographic and topographic features.
    - Narrower double-line streams and rivers.
    - Single-line streams and rivers.
    - Smaller ponds.
    - Culverts and other drainage structures.
    - Retaining walls.
    - Hydrologic areas (for example, swamp or marsh).
    - Appropriate integration of additional features into delivered DEMs.
- Extracted Buildings (PolygonZ).
  - Footprints with maximum elevation or height above ground as an attribute.
- Other products as defined by requirements and agreed upon before a funding commitment.

For appendices 2, 3, and 4, please refer to Lidar Base Specification v. 1.3