1.0 Conversion Factors

Altitude and Elevation, as used in this report, refers to the distance above the geoid, unless specifically referenced to the ellipsoid.

Height, as used in this report, refers to the height above ground.

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre
square meter (m^2)	10.76	square foot (ft^2)
hectare (ha)	2.471	acre
hectare (ha)	0.003861	square mile (mi^2) = 640 acres = 1 section
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861022	square mile (mi^2)

2.0 Abbreviations and Acronyms

ASPRS	American Society for Photogrammetry and Remote Sensing
CLICK	Center for Lidar Information, Coordination, and Knowledge
CONUS	Conterminous United States
CORS	Continuously Operating Reference Stations
CVA	Consolidated Vertical Accuracy
DEM	Digital Elevation Model
DSM	Digital Surface Models
DTED	digital terrain elevation data
DTM	digital terrain model
EDNA	Elevation Derivatives for National Applications
EPSG	European Petroleum Survey Group
FGDC	Federal Geographic Data Committee
FOV	field of view
FVA	Fundamental Vertical Accuracy
GB	gigabyte
GPS	Global Positioning System
GSD	ground sample distance
H&H	hydraulic and hydrologic
IFSAR	Interferometric Synthetic Aperature Radar
lidar	light detection and ranging
IMU	Inertial Measurement Unit
NAD83	North American Datum of 1983
NAVD88	North American Vertical Datum of 1988
NDEP	National Digital Elevation Program
NEEA	National Enhanced Elevation Assessment
NED	National Elevation Dataset
NGP	National Geospatial Program
NGS	National Geodetic Survey
NIR	near infra-red
NIST	National Institute of Standards and Technology
NPS	Nominal Pulse Spacing
NSRS	National Spatial Reference System
NSSDA	National Standards for Spatial Data Accuracy
OCONUS	Outside the Conterminous United States
QA/QC	Quality Assurance/Quality Control
RMSE	Root Mean Square Error
SOM	State of Michigan
SVA	Supplemental Vertical Accuracy
TIN	Triangulated Irregular Network
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator
XML	eXtensible Markup Language

3.0 Introductory Material

3.1 Purpose and Scope

The State of Michigan (SOM) intends to use this specification to acquire and procure light detection and ranging (lidar) data, and to create consistency across all SOM and partner funded lidar collections. Most of the information in this specification was extracted from the USGS Lidar Base Specification Version 1.0 (*http://pubs.usgs.gov/tm/11b4/TM11-B4.pdf; Heidemann, Hans Karl, 2012, Lidar base specification version 1.0, U.S. Geological Survey Techniques and Methods, book 11, chap. B4, 63 p.).* While changes have been made to various sections to improve the applicability for the SOM and its partners, the specification still meets USGS standards. Also, some sections have been purposely excluded but still apply to this specification. In addition to reviewing this document, vendors responding to Request for Proposals for SOM lidar data collection should reference the following sections in the USGS Lidar Base Specification Version 1.0:

- Glossary (for terminology)
- Appendix 4. Lidar Metadata Example
- Appendix 5. Lidar Metadata Template

It must be emphasized that this is a base specification, defining minimum parameters for acceptance of the acquired lidar data. It is expected that local conditions in any given project area, specialized applications for the data, or the preferences of cooperators, may mandate more stringent requirements. The SOM encourages the collection of more detailed, accurate, or value-added data. A list of common upgrades to the minimum requirements defined in this report is provided in appendix 1.

3.2 Applicability

These specifications and guidelines are applicable to lidar data and deliverables supported in whole or in part, with either financial or in-kind contributions, by the SOM and/or the USGS.

3.3 Warranty Against Data Defects

Defects in imagery collection that are reported by the customer within 90 days shall be corrected by re-acquisition and re-processing. Defects in image processing reported by the customer within 12 months shall be corrected by re-processing.

4.0 Collection

4.1 Multiple Discrete Returns

Data collection must be capable of at least three returns per pulse. Full waveform collection is acceptable and welcomed; however, waveform data are regarded as supplemental information. Deriving and delivering multiple discrete returns is required in all cases.

4.2 Intensity Values

Intensity values are required for each return. The values are to be recorded in the .las files in their native radiometric resolution.

4.3 Nominal Pulse Spacing (NPS)

A NPS of at least 2 points per square meter is required. Dependent on the local terrain and land cover conditions in the project area, a greater point density may be required on specific projects. Assessment of the NPS will be made against single swath, first-return only data, located within the geometrically usable center portion (typically 90 percent) of each swath, acceptable data voids excluded. NPS will be calculated as the square root of the average area per point. Average along-track and cross-track point spacing should be comparable (within 10 percent).

In general, the target NPS for a project should not be achieved through swath overlap or multiple passes. Such collection techniques may be permitted with prior approval.

4.4 Data Voids

Data voids within a single swath are not acceptable, except in the following circumstances:

- Where caused by water bodies,
- Where caused by areas of low near infra-red (NIR) reflectivity such as asphalt or composition roofing, or
- Where appropriately filled-in by another swath.

4.5 Spatial Distribution

The spatial distribution of geometrically usable points is expected to be uniform. Although it is understood that lidar instruments do not produce regularly gridded points, collections should be planned and executed to produce a first-return point cloud that approaches a regular lattice of points, rather than a collection of widely spaced high density profiles of the terrain. The uniformity of the point density throughout the dataset is important and will be assessed using the following steps:

- Generating a density grid from the data with cell sizes equal to the design NPS times 2, using a radius equal to the design NPS.
- Ensuring at least 90 percent of the cells in the grid contain at least one lidar point.
- The assessment is to be made against individual (single) swaths, using only the first-return points located within the geometrically usable center portion (typically 90 percent) of each swath.
- Excluding acceptable data voids previously identified in this specification.

Note: This requirement may be relaxed in areas of substantial relief where it is impractical to maintain a consistent and uniform distribution.

Note: The process described in this section relates only to the uniformity of the point distribution. It in no way relates to, nor can it be used for the assessment of point density or NPS.

4.6 Scan Angle

Scan angle will support horizontal and vertical accuracy within the requirements as specified in the next two sections. See Appendix 2 for additional information.

Note: This requirement primarily is applicable to oscillating mirror lidar systems. Other instrument technologies may be exempt from this requirement.

4.7 Vertical Accuracy

Vertical accuracy of the lidar data will be assessed and reported in accordance with the guidelines developed by the National Digital Elevation Program (NDEP) and subsequently adopted by the American Society for Photogrammetry and Remote Sensing (ASPRS). Complete definitions for vertical accuracy assessments are in Section 1.5 of the NDEP Elevation Guidelines (NDEP, 2004). Additionally, accuracy will be reported according to Quality Level (QL) as described in the National Enhanced Elevation Assessment (NEEA) revised on 3/29/2012 (http://www.dewberry.com/Consultants/GeospatialMapping/FinalReport-NationalEnhancedElevationAssessment). See table 1.

The minimum vertical accuracy requirement for the **unclassified lidar point cloud**, using the NDEP/ASPRS methodology, is listed below:

- Fundamental Vertical Accuracy (FVA)<= 18.5 centimeters (cm) Accuracy$_z$ (ACC$_z$), 95 percent (9.25 cm Root Mean Square Error (RMSE)). This equates to Quality Level 2 (QL 2) in table 1.

The minimum vertical accuracy requirements for the **derived DEM**, using the NDEP/ASPRS methodology are listed below:

- Fundamental Vertical Accuracy (FVA)<= 18.5 centimeters (cm) Accuracy$_z$ (ACC$_z$), 95 percent (9.25 cm Root Mean Square Error (RMSE)). Again, this equates to Quality Level 2 (QL 2) in table 1.

Table 1. Quality Levels for LiDAR Horizontal Resolution and Vertical Accuracy

Elevation Quality Levels (QL)	Source	Horizontal Resolution Terms		Vertical Accuracy Terms	
		Point Density	Nominal Pulse Spacing (NPS)	Vertical RMSE$_z$	Equivalent Contour Accuracy
QL 1	LiDAR	8 pts/m^2	0.35 m	9.25 cm	1-ft
QL 2	LiDAR	2 pts/m^2	0.7 m	9.25 cm	1-ft
QL 3	LiDAR	1 – 0.25 pts/m^2	1 – 2 m	≤18.5 cm	2-ft

- Consolidated Vertical Accuracy (CVA)<= 26.5cm, 95th percentile, and

- Supplemental Vertical Accuracy (SVA)<= 26.5 cm, 95th percentile. Point cloud data accuracy is to be tested against a Triangulated Irregular Network (TIN) constructed from lidar points in clear and open areas. A clear and open area can be characterized with respect to topographic and ground cover variation such that a minimum of 5 times the NPS exists with less than 1/3 of the RMSE$_z$ deviation from a low-slope plane. Slopes that exceed 10 percent should be avoided. Ground that has been plowed or otherwise disturbed is not acceptable. All tested locations should be photographed showing the position of the tripod and the surrounding area ground condition.
- Each land cover type representing 10 percent or more of the total project area must be tested and reported with an SVA. In areas where a land cover category is something other than forested or dense urban, the tested point should not have any obstructions 45 degrees above the horizon to ensure a sufficient TIN surface. Additionally, tested areas should not be in proximity to low NIR reflective surfaces such as asphalt or

composition roofing materials.

The SVA value is provided as a target. It is understood that in areas of dense vegetation, swamps, or extremely difficult terrain, this value may be exceeded.

The CVA value is a requirement that must be met, regardless of any allowed "busts" in the SVA(s) for individual land cover types within the project.

Checkpoints for each assessment (FVA, CVA, and all SVAs) are required to be well-distributed throughout the land cover type, for the entire project area. See Glossary for definition of well-distributed.

Exceptions: These requirements may be relaxed in cases:

- Where there exists a demonstrable and substantial increase in cost to obtain this accuracy.
- Where an alternate specification is needed to conform to previously contracted phases of a single larger overall collection effort, for example, multi-year statewide collections.
- Where the SOM agrees that it is reasonable and in the best interest of all stakeholders to use an alternate specification.

4.8 Relative Accuracy

The requirements for relative accuracy are listed below:

- Within individual swaths:<= 7 cm RMSEz
- Within overlap between adjacent swaths:<=10 cm RMSEz

4.9 Flightline Overlap

Flightline overlap of 10 percent or greater is required to ensure there are no data gaps between the usable portions of the swaths. Collections in high relief terrain are expected to require greater overlap. Any data with gaps between the geometrically usable portions of the swaths will be rejected.

4.10 Collection Area

Data collection will cover the entire project area as defined by SOM. SOM will provide AOI boundaries in ESRI Shapefile format. All AOI shapefiles will include a buffer of at least 100 meters. Data delivered to the SOM will include all areas specified by the AOI shapefiles.

4.11 Collection Conditions

Atmospheric conditions must be cloud and fog-free between the aircraft and ground during all collection operations.

Ground conditions must be snow free. Very light, undrifted snow may be acceptable in special cases, with prior written approval from the SOM.

Water conditions must be free of any unusual flooding or inundation, except in cases where the goal of the collection is to map the inundation.

Leaf-off vegetation conditions are preferred. If project delays are caused by the SOM and resulting conditions are deemed acceptable to meet or exceed the specifications for anticipated ground point returns, the program (data collection) may be permitted to continue with prior approval from the SOM.

5.0 Data Processing and Handling

5.1 ASPRS LAS File Format

All processing should be carried out with the understanding that all point deliverables are required to be in fully compliant LAS format, v1.1 or v1.2. Deliverables in LAS v1.4 will be considered an upgrade. The version selected must be used for all LAS deliverables in the project. Data producers are encouraged to review the appropriate LAS specification in detail (ASPRS, 2011).

5.2 Full Waveform

If full waveform data are collected, delivery of the waveform packets is required in LAS v1.4. Deliverables with waveform data are to use external auxiliary files with the extension .wdp for the storage of waveform packet data. See the appropriate LAS Specification for additional information (ASPRS, 2011).

5.3 Global Positioning System (GPS) Times

GPS times are to be recorded as Adjusted GPS Time, at a precision sufficient to allow unique timestamps for each pulse. Adjusted GPS Time is defined to be Standard (or satellite) GPS time minus $1*10^9$. See the appropriate LAS Specification for more detail (ASPRS, 2011).

5.4 Datums

All data collected must be tied to the datums listed below:

- **Horizontal Datum:** Most current realization of the North American Datum of 1983 (NAD83), including epoch, as determined by the National Geodetic Survey (NGS), and which existing Continuously Operating Reference Station (CORS) data is referenced. As of 10/1/2012 the horizontal datum to which CORS is referenced is NAD83(CORS96); epoch 2002.0. This is expected to change to NAD83(2011); epoch 2010.0 in late 2012 or early 2013.
- **Vertical Datum:** Data must be referenced to the North American Vertical Datum of 1988 (NAVD 88).
- **Geoid Model:** The most current National Geodetic Survey (NGS)-approved geoid model is required to perform conversions from ellipsoidal heights to orthometric heights. As of 10/1/2012 the most current Geoid Model as defined by the NGS is GEOID12A.

5.5 Coordinate Reference System

The SOM required Coordinate Reference System is as follows:

Coordinate Reference System: Michigan State Plane
Horizontal Datum: Most current realization of NAD83 (see 5.4 above)
Horizontal Units: International Feet
Vertical Datum: NAVD88
Vertical Units: International Feet
Vertical Reference: Orthometric Heights
Geoid Model: Most Current NGS Geoid model

Each discrete project is to be processed using the single predominant State Plane zone for the overall collection area (e.g., North, Central, South).

5.6 Units of Reference

All references to the unit of measure "Feet" and "Foot" must specify "International" or "Intl", U.S. survey feet are not to be used as a unit of measure.

5.7 Swath Identification

Each swath will be assigned a unique File Source ID. It is required that the Point Source ID field for each point within each LAS swath file be set equal to the File Source ID before any processing of the data. Refer to the appropriate LAS Specification (ASPRS, 2011).

5.8 Point Families

Point families (multiple return "children" of a single "parent" pulse) shall be maintained intact through all processing before tiling. Multiple returns from a given pulse will be stored in sequential (collected) order.

5.9 Swath Size and Segmentation

Swath files will be 2 gigabytes (GB) in size or less. Long swaths (those which result in a LAS file larger than 2 GB) will be split into segments no greater than 2 GB each.

- Each sub-swath will retain the original File Source ID of the original complete swath.
- Points within each sub-swath will retain the Point Source ID of the original complete swath.
- Each sub-swath file will be named identically to the original complete swath, with the addition of an ordered alphabetic suffix to the name ("-a", "-b" … "-n"). The order of the named sub-swaths shall be consistent with the collection order of the points ("-a" will be the chronological beginning of the swath; "-n" will be the chronological end of the swath).
- Point families shall be maintained intact within each sub-swath.
- Sub-swaths should be broken at the edge of the scan line.
- Other swath segmentation approaches may be acceptable, with prior approval.

5.10 Scope of Collection

All collected swaths are to be delivered as part of the Calibrated Raw Data Deliverable. This includes calibration swaths and cross-ties. This in no way requires or implies that calibration swath data are to be included in product generation. All collected points are to be delivered. No points are to be deleted from the swath LAS files. Excepted from this are extraneous data outside of the buffered project area (aircraft turns, transit between the collection area and airport, transit between fill-in areas, and the like). These points may be permanently removed. Busted swaths that are being completely discarded by the vendor and re-flown do not need to be delivered.

5.11 Use of the LAS Withheld Flag

Outliers, blunders, noise points, geometrically unreliable points near the extreme edge of the swath, and other points the vendor deems unusable are to be identified using the Withheld flag, as defined in the LAS specification.

This applies primarily to points that are identified during pre-processing or through automated post-processing routines.

If processing software is not capable of populating the Withheld bit, these points may be identified using Class=11.

Noise points subsequently identified during manual Classification and Quality Assurance/Quality Control (QA/QC) may be assigned the standard LAS classification value for Noise (Class=7), regardless of whether the noise is "low" or "high" relative to the ground surface.

5.12 Point Classification

- ALL points not identified as Withheld are to be classified.
- No points in the Classified LAS deliverable will be assigned Class=0.
- Use of the ASPRS/LAS Overlap classification (Class=12) is prohibited.

If overlap points are required to be differentiated by the data producer or cooperating partner, they must be identified using a method that does not interfere with their classification:

- Overlap points are tagged using Bit:0 of the User Data byte, as defined in the LAS specification. (SET=Overlap).
- Overlap points are classified using the Standard Class values + 16.
- Other techniques as agreed upon in advance.

The technique used to identify overlap must be clearly described in the project metadata files. Note: A standard bit flag for identification of overlap points has been included in LAS v1.4, released on November 14, 2011. This is only relevant for full waveform data since it must be delivered in LAS v1.4.

5.13 Positional Accuracy Validation

Before classification of and development of derivative products from the point cloud, verification of the vertical accuracy of the point cloud, absolute and relative, is required. The Fundamental Vertical Accuracy (absolute) is to be assessed in clear, open areas as described in the section called Vertical Accuracy above. Swath-to-swath and within swath accuracies (relative) are to be documented. A detailed report of this validation process is a required deliverable.

5.14 Classification Accuracy

It is required that due diligence in the classification process will produce data that meet the following tests:

- Following classification processing, no non-withheld points should remain in Class 0.
- Within any 1 kilometer (km) x 1 km area, no more than 2 percent of non-withheld points will possess a demonstrably erroneous classification value.

Note: These requirements may be relaxed to accommodate collections in areas where the SOM agrees classification to be particularly difficult.

5.15 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.

5.16 Tiles

Note: This section assumes a projected coordinate reference system.

A single non-overlapped tiling scheme (the Project Tiling Scheme) will be established and agreed upon by the data producer and the SOM before collection (file size will be a determinant). This scheme will be used for ALL tiled deliverables.

- Tile size is required to be an integer multiple of the cell size of raster deliverables.
- Tiles are required to be sized using the same units as the coordinate system of the data.

- Tiles are required to be indexed in X and Y to an integer multiple of the tile's X-Y dimensions.
- All tiled deliverables will conform to the Project Tiling Scheme, without added overlap.
- Tiled deliverables will edge-match seamlessly and without gaps.

Note: SOM recommends a tiling scheme of 10,000 feet x 10,000 feet. This may be changed after discussions between SOM and the vendor.

6.0 Hydro-Flattening

Note: Please refer to appendix 3 for reference information on hydro-flattening.

Hydro-flattening pertains only to the creation of derived DEMs. Breaklines may be used to help classify the point data. The goal of the SOM, through use of hydro-flattening, is to enhance the cartographic and aesthetic value of derived DEMs (and derived contours) concerning water features. The goal is not to produce either Hydro-conditioned or Hydro-enforced DEMs. To accomplish this goal will require that ponds and lakes (of the size specified) include shore breaklines and/or polygons possessing a single elevation representing the current water level. Inland rivers and streams (of the size specified) will be addressed through creation of breaklines on either shore, and contain a descending elevation in the direction of flow as required to accurately reflect the current elevation of the water surface.

6.1 Inland Ponds and Lakes

- 2 acres or greater surface area (approximately equal to a round pond 350 feet in diameter) at the time of collection.
- Flat and level water bodies (single elevation for every bank vertex defining a given water body).
- The entire water surface edge must be at or below the immediately surrounding terrain. The presence of floating water bodies will be cause for rejection of the deliverable.
- Long impoundments such as reservoirs or inlets, whose water surface elevations drop when moving downstream, are required to be treated as rivers.

Note: Feature size thresholds may be increased by the SOM if the current thresholds prove to be prohibitively expensive.

6.2 Inland Streams and Rivers

- 100 feet nominal width: This should not unnecessarily break a stream or river into multiple segments. At times it may squeeze slightly below 100 feet for short segments. Data producers should use their best professional cartographic judgment.
- Flat and level bank-to-bank (perpendicular to the apparent flow centerline); gradient to follow 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, it is appropriate to represent the water surface as it exists in nature, while maintaining an aesthetic cartographic appearance.
- The entire water surface edge must be at or below the immediately surrounding terrain.
- Stream channels are required to break at road crossings (culvert locations). The roadway over a culvert should be continuous. A culvert, regardless of size, is defined as having earth between the road surface and the top of the structure.

- Bridges are required to be removed from the DEM. Streams and rivers should be continuous at bridge locations. Bridges are defined as having an elevated deck structure that does not rest on earth.
- When the identification of a structure such as a bridge or culvert cannot be made reliably, the feature should be regarded as a culvert.

6.3 Great Lakes

- Water surface is to be flat and level.
- The entire water surface edge must be at or below the immediately surrounding terrain.

6.4 Islands

- Permanent islands 1 acre or larger shall be delineated within all water bodies. This includes the Great Lakes.

6.5 Single-Line Streams

Cooperating partners may require collection and integration of single-line streams within their lidar projects. Although the SOM does not require these breaklines be collected or integrated, it does require that if used and incorporated into the DEMs, the following guidelines are met:

- All vertices along single-line stream breaklines are at or below the immediately surrounding terrain.
- Single-line stream breaklines are not to be used to introduce cuts into the DEM at road crossings (culverts), dams, or other such features. This is hydro-enforcement and as discussed in appendix 3 will create a non-topographic DEM.
- All breaklines used to modify the surface are to be delivered to the SOM with the DEMs.

7.0 Deliverables

7.1 Metadata

The term “metadata” refers to all descriptive information about the project. This includes textual reports, graphics, supporting shapefiles, and Federal Geographic Data Committee (FGDC)-compliant metadata files. Metadata deliverables include the following items:

- Collection report detailing mission planning and flight logs.
- Survey report detailing the collection of control and reference points used for calibration and QA/QC.
- Processing report detailing calibration, classification, and product generation procedures including methodology used for breakline collection and hydro-flattening if hydro-flattening is requested (see the section called Hydro-Flattening and appendix 3 for more information on hydro-flattening).
- QA/QC Reports (detailing the analysis, accuracy assessment and validation of the following:
  - Point data (absolute, within swath, and between swath)
  - Bare-earth surface (absolute)
  - Other optional deliverables as appropriate
- Control and calibration points: All control and reference points used to calibrate, control, process, and validate the lidar point data or any derivative products that are to be delivered in report form including appropriate from/to diagrams and photographs.
- Georeferenced, digital spatial representation of the precise extents of each delivered dataset. This should reflect the extents of the actual lidar source or derived product data, exclusive of TIN artifacts or raster NODATA areas. A

union of tile boundaries or minimum bounding rectangles is not acceptable. ESRI Polygon shapefile or geodatabase is preferred.

- Product metadata [FGDC compliant, eXtensible Markup Language (XML) format metadata]. Each Lift: Describing the extents of the lift, the swaths included in the lift, locations of GPS base stations and control for the lift, preprocessing and calibration details for the lift, adjustment and fitting processes applied to the lift in relation to other lifts, and other lift-specific information.
- Each tiled deliverable product group:
  - Raw point data (calibrated-unclassified)
  - Classified point data
  - Bare-earth DEMs
  - Breaklines (if generated)
  - Other datasets delivered under the contract (Hydro-flattened and/or Hydro-enforced DEM, intensity images, and others)
- FGDC compliant metadata must pass the FGDC metadata parser (mp) with no errors.

Note: Please refer to the metadata templates in appendixes 4 and 5 of the USGS Lidar Base Specification Version 1.0 for additional information.

7.2 Raw Point Cloud

Delivery of the raw point cloud, otherwise known as the **Calibrated-unclassified point cloud**, is a standard requirement for SOM lidar projects. Raw point cloud deliverables include the following items:

- All swaths, returns, and collected points, fully calibrated and adjusted to ground, by swath.
  - Withheld points should not be included in this deliverable but are required in the Classified Point Cloud.
- Fully compliant LAS v1.1 or v1.2 (or v1.4 if full waveform data), Point Data Record Format must conform to delivered LAS version.
- If provided as an upgrade to v1.1/v1.2, LAS v1.4 deliverables with waveform data are to use external auxiliary files with the extension .wdp for the storage of waveform packet data. See appropriate LAS Specification for additional information (ASPRS 2011).
- Correct and properly formatted georeference information must be included in all LAS file headers.
- GPS times are to be recorded as Adjusted GPS Time, at a precision sufficient to allow unique timestamps for each pulse.
- Intensity values (native radiometric resolution).
- One file per swath, one swath per file, file size not to exceed 2 GB, as described under the section called Swath Size and Segmentation above.
- Vertical accuracy requirements using the NDEP/ASPRS methodology for the point cloud are FVA<= 18.5 cm ACCz, 95-percent confidence level (9.25 cm RMSEz).

7.3 Classified Point Cloud

Delivery of classified point cloud data is a standard requirement for SOM lidar projects. Specific scientific research projects may be exempt from this requirement. Classified point cloud deliverables include the following items:

- All project swaths, returns, and collected points, fully calibrated, adjusted to ground, and classified, by tiles. Project swaths exclude calibration swaths, cross-ties, and other swaths not used, or intended to be used, in product generation.

- Fully compliant LAS v1.1 or v1.2 (or v1.4 if full waveform data), Point Data Record Format must conform to delivered LAS version.
- If provided as an upgrade to v1.1/v1.2, LAS v1.4 deliverables with waveform data are to use external auxiliary files with the extension .wdp for the storage of waveform packet data. See appropriate LAS Specification for additional information (ASPRS 2011).
- Correct and properly formatted georeference information must be included in all LAS file headers.
- GPS times are to be recorded as Adjusted GPS Time, at a precision sufficient to allow unique timestamps for each pulse.
- Intensity values (native radiometric resolution).
- Tiled delivery, without overlap, using Project Tiling Scheme.
- Classification Scheme (minimum) as listed in table 2.
- Vertical accuracy requirements using the NDEP/ASPRS methodology for the point cloud are FVA<= 18.5 cm ACCz, 95-percent confidence level (9.25 cm RMSEz).

Table 2. Minimum Classified Point Cloud Classification Scheme

Code	**Description**
1	Not ground (all returns deemed not ground returns)
2	Bare-earth ground (DEM)
7*	Noise(low or high; manually identified if needed)
9	Water (if Hydro-flattened or Hydro-enforced DEM requested)
10**	Ignored Ground (if Hydro-flattened or Hydro-enforced DEM requested; Breakline proximity)
11	Withheld (if the Withheld bit is not implemented in processing software)

***Class 7, Noise, is included as an adjunct to the Withheld bit. All noise points are to be identified using one of these two methods.**

****Class 10, Ignored Ground, is for points previously classified as bare-earth but whose proximity to a subsequently added breakline requires that it be excluded during Digital Elevation Model (DEM) generation.**

7.4 Bare-Earth Surface Digital Elevation Model (DEM)

Delivery of a bare-earth DEM in both Raster and ASCII format is required. Bare-earth surface deliverables include the following items:

- Bare-earth DEM, generated through use of a triangulated irregular network (TIN), to the limits of the Buffered Project Area.
    - Raster data file with cell size no greater than 3 feet, and no less than the design Nominal Pulse Spacing (NPS).
        - Delivery in an industry-standard, GIS-compatible, 32-bit floating point raster format (ERDAS .IMG preferred).
    - ASCII text file with grid spacing no greater than 3 feet, and no less than the design Nominal Pulse Spacing (NPS).
- Georeference information shall be included in each raster and ASCII file.
- Tiled delivery, without overlap.
- DEM tiles will show no edge artifacts or mismatch. A quilted appearance in the overall project DEM surface, whether caused by differences in processing quality or character between tiles, swaths, lifts, or other non-natural

divisions, will be cause for rejection of the entire deliverable.

- Void areas (for example, areas outside the Buffered Project Area but within the tiling scheme) shall be coded using a unique NODATA value. This value shall be identified in the appropriate location within the raster file header or external support files (for example, .aux).

- Vertical accuracy of the bare-earth surface will be assessed and reported in accordance with the guidelines developed by the NDEP and subsequently adopted by the ASPRS. The complete guidelines are in Section 1.5 of the NDEP Guidelines (NDEP, 2004).
- The following thresholds represent the minimum vertical accuracy requirements using the NDEP/ASPRS methodology:
    - FVA<= 18.5 cm ACCz, 95 percent Confidence Level (9.25 cm RMSEz)
    - CVA<= 26.5 cm, 95th percentile
    - SVA<= 26.5 cm, 95th percentile
    - All QA/QC analysis materials and results are to be delivered to the SOM.
    - Depressions (sinks), natural or man-made, are not to be filled (as in hydro-conditioning and hydro-enforcement).

7.5 Data Upgrade: Hydro-flattened Digital Elevation Model (DEM) and Breaklines/Polygons

Delivery of a Hydro-flattened DEM in both Raster and ASCII format is required. Hydro-flattened surface deliverables include the following items:

- Hydro-flattened DEM, generated to the limits of the Buffered Project Area.
    - Raster data file with cell size no greater than 3 feet, and no less than the design Nominal Pulse Spacing (NPS).
        - Delivery in an industry-standard, GIS-compatible, 32-bit floating point raster format (ERDAS .IMG preferred).
    - ASCII text file with grid spacing no greater than 3 feet, and no less than the design Nominal Pulse Spacing (NPS).
- Georeference information shall be included in each raster and ASCII file.
- Tiled delivery, without overlap.
- DEM tiles will show no edge artifacts or mismatch. A quilted appearance in the overall project DEM surface, whether caused by differences in processing quality or character between tiles, swaths, lifts, or other non-natural divisions, will be cause for rejection of the entire deliverable.
- Void areas (for example, areas outside the Buffered Project Area but within the tiling scheme) shall be coded using a unique NODATA value. This value shall be identified in the appropriate location within the raster file header or external support files (for example, .aux).
- Vertical accuracy of the DEM must match the vertical accuracy of the point data.
- Depressions (sinks), natural or man-made, are not to be filled (as in hydro-conditioning and hydro-enforcement).
- Water bodies (ponds and lakes), wide streams and rivers (double-line), and other non-tidal water bodies as defined in the section called Hydro-flattening are to be hydro-flattened within the DEM. Hydro-flattening shall be applied to all water impoundments, natural or man-made, that are larger than 2 acres in area (approximately equal to a round pond 350 feet in diameter), to all streams that are nominally wider than 100 feet, and to all Great Lakes areas. The methodology used for hydro-flattening is at the discretion of the data producer.

Note: Please refer to the section called Hydro-Flattening and appendix 3 for detailed discussions of hydro-flattening.

Delivery of the breaklines generated during hydro-flattening is a standard requirement for SOM lidar projects if Hydro-flattening was completed. If hydro-flattening is achieved through other means, this section may not apply. Breakline (and/or polygon) deliverables include the following items:

- Breaklines defining the limits and elevations of the water bodies shall be developed to the limit of the Buffered Project Area.
- All breaklines developed for use in hydro-flattening shall be delivered as an ESRI feature class (PolylineZ or PolygonZ format, as appropriate to the type of feature represented and the methodology used by the data producer). Shapefile or geodatabase is required.
- Each feature class or shapefile will include properly formatted and accurate georeference information in the standard location. All shapefiles must include a correct and properly formatted *.prj file.
- Breaklines must use the same coordinate reference system (horizontal and vertical) and units as the lidar point delivery.
- Breakline delivery may be as a continuous layer or in tiles, at the discretion of the data producer. In the case of tiled deliveries, all features must edge-match exactly across tile boundaries in both the horizontal (*X*-*Y*) and vertical (*Z*) spatial locations.

If Hydro-flattening is selected as an upgrade, the Classified Point Cloud Data (7.3) must include Water points.

7.6 Data Upgrade: Hydro-Enforced Digital Elevation Model (DEM) and Breaklines/Polygons

Delivery of a Hydro-enforced DEM in both Raster and ASCII format is required. Deliverables include the following items:

- Hydro-enforced DEM, generated to the limits of the Buffered Project Area.
    - Raster data file with cell size no greater than 3 feet, and no less than the design Nominal Pulse Spacing (NPS).
        - Delivery in an industry-standard, GIS-compatible, 32-bit floating point raster format (ERDAS .IMG preferred).
    - ASCII text file with grid spacing no greater than 3 feet, and no less than the design Nominal Pulse Spacing (NPS).
- Georeference information shall be included in each raster and ASCII file.
- Tiled delivery, without overlap.
- Hydro-enforced DEM tiles will show no edge artifacts or mismatch. A quilted appearance in the overall project DEM surface, whether caused by differences in processing quality or character between tiles, swaths, lifts, or other non-natural divisions, will be cause for rejection of the entire deliverable.
- Void areas (for example, areas outside the Buffered Project Area but within the tiling scheme) shall be coded using a unique NODATA value. This value shall be identified in the appropriate location within the raster file header or external support files (for example, .aux).
- Vertical accuracy of the DEM must match the vertical accuracy of the point data.

Note: Reference Appendix 3 for Hydrologically-Enforced definition, and requirements.

Delivery of the breaklines generated during hydro-enforcement is a standard requirement for SOM lidar projects if Hydro-enforcement was completed. Breakline (and/or polygon) deliverables include the following items:

- Breaklines defining the limits and elevation of water bodies shall be developed to the limit of the Buffered Project

Area.

- All breaklines developed for use in hydro-enforcement shall be delivered as an ESRI feature class (PolylineZ or PolygonZ format, as appropriate to the type of feature represented and the methodology used by the data producer). Shapefile or geodatabase is required.
- Each feature class or shapefile will include properly formatted and accurate georeference information in the standard location. All shapefiles must include a correct and properly formatted *.prj file.
- Breaklines must use the same coordinate reference system (horizontal and vertical) and units as the lidar point delivery. Breakline delivery may be as a continuous layer by Area of Interest or in tiles, at the discretion of the data producer. In the case of tiled deliveries, all features must edge-match exactly across tile boundaries in both the horizontal (*X*-*Y*) and vertical (*Z*) spatial locations.

If Hydro-enforcement is selected as an upgrade, the Classified Point Cloud Data (7.3) must include Water points.

7.7 Data Upgrade: Lidar Intensity Images

Lidar intensity images are georeferenced raster files with each pixel representing the intensity of the Lidar return.

- Lidar intensity image, generated to the limits of the Buffered Project Area.
  - Raster data file with cell size no greater than 3 feet.
    - 8-bit GeoTIFF file format required.
- Georeference information shall be included in each raster file.
- Tiled delivery, without overlap.
- Void areas (for example, areas outside the Buffered Project Area but within the tiling scheme) shall be coded using a NODATA value.

References Cited

American Society for Photogrammetry & Remote Sensing (ASPRS), 2011, LAS specification (Version 1.4–R12): Bethesda, Md., ASPRS, 27 p. Available online at *http://www.asprs.org/Committee-General/LASer-LAS-File-Format-Exchange-Activities.html*.

American Society for Photogrammetry & Remote Sensing (ASPRS), 2004. Vertical accuracy reporting for lidar–Version 1.0, 20 p. (Also available at *http://www.asprs.org/a/society/committees/lidar/Downloads/Vertical_Accuracy_Reporting_for_ Lidar_Data.pdf*.)

Gesch, D.B., 2007, The National Elevation Dataset, chap. 4 *of* Maune, D., ed., Digital elevation model technologies and applications—the DEM user's manual, (2nd ed.): Bethesda, Md., American Society for Photogrammetry and Remote Sensing,
p. 99–118. (Also available at *http://topotools.cr.USGS.gov/pdfs/Gesch_Chp_4_Nat_Elev_Data_2007.pdf*.)

Maune, D.F., 2007, Definitions, *in* Digital Elevation Model Technologies and Applications—The DEM Users' Manual, (2nd ed.), American Society for Photogrammetry and Remote Sensing, Bethesda, Md., p. 550–551

National Digital Elevation Program (NDEP), 2004, Guidelines for Digital Elevation Data—Version 1: 93 p. (Also available at *http://www.ndep.gov/NDEP_Elevation_Guidelines_Ver1_10May2004.pdf*.)

Stoker, J.M., Greenlee, S.K., Gesch, D.B., and Menig, J.C., 2006, CLICK—the new USGS center for lidar information coordi-nation and knowledge: Photogrammetric Engineering and Remote Sensing, v. 72, no. 6, p. 613–616. (Also available at *http:// www.asprs.org/a/publications/pers/2006journal/june/highlight.pdf*.)

USGS Federal Geographic Data Committee, 1998, Geospatial Positioning Accuracy Standards Part 3: National Standard for Spatial Data Accuracy, 20 p. (Also available at *http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/ part3/chapter3*.)

Appendix 1. Common Data Upgrades

- Independent 3rd-Party QA/QC by another Architecture & Engineering (AE) Contractor (encouraged)
- Lower NPS (greater point density)
- Increased Vertical Accuracy
- Full Waveform collection and delivery
- Additional Environmental Constraints
    - Interpolation based on 1st-Returns
    - Interpolation based on All-Returns, summed
- Detailed Classification (additional classes; e.g., vegetation levels)
- Hydro-Enforced DEMs as an additional deliverable
- Hydro-Conditioned DEMs as an additional deliverable
- Breaklines (PolylineZ and PolygonZ) for single-line hydrographic features
    - Narrow streams not collected as double-line, culverts, and other similar features, including appropriate integration into delivered DEMs
    - Breaklines (PolylineZ and PolygonZ) for other features (to be determined)
    - Including appropriate integration 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 in advance of funding commitment

Appendix 2. Guidelines

Scan Angle

For oscillating mirror lidar systems, the total field of view should not exceed 40 degrees (within 20 degrees of nadir). State of Michigan (SOM) quality assurance on collections performed using scan angles wider than 34 degrees will be particularly rigorous in the edge-of-swath areas. Lidar systems that use rotating mirrors/prisms may be exempted from this guideline.

Swath Size

The processing report shall include detailed information on swath segmentation sufficient to allow reconstruction of the original swaths if needed.

Non-Tidal Boundary Waters

The elevation along the edge or edges should behave consistently throughout the project. May be a single elevation (for example, a lake) or gradient (for example, a river), as appropriate. If unusual changes in water surface elevation occur during the course of the collection, then the surface may be treated as a tidal boundary, as described in the next section. The reason for the changes must be documented in the project metadata.

Breaklines and Hydro-Flattening

The SOM does not require any particular process or methodology be used for hydro-flattening or for breakline collection, extraction, or integration. However, if breaklines are developed, the following general guidelines must be adhered to:

- Bare-earth lidar points that are in close proximity breaklines should be excluded from the DEM generation process. This is analogous to the removal of masspoints for the same reason in a traditional photogrammetrically compiled digital terrain model (DTM). The proximity threshold for reclassification as Ignored Ground is at the discretion of the data producer, but in general should not exceed the nominal pulse spacing (NPS). These points are to be retained in the delivered lidar point dataset and shall be reclassified as Ignored Ground (class value = 10) so that they may be subsequently identified.
- Delivered data must be sufficient for the SOM to effectively recreate the delivered DEMs using the lidar points and breaklines without substantial editing.
- The goal of hydro-flattening is to produce a topographic DEM that, with respect to water surfaces, resembles a DEM derived from traditional photogrammetric methods. Best professional judgment should be used to achieve this end.

Appendix 3. Hydro-Flattening Reference

The subject of modifications to lidar-based digital elevation models (DEM) is somewhat new and there is substantial variation in the understanding of the topic across the industry.

The information presented here is not meant to supplant other reference materials and it should not be considered authoritative beyond its intended scope.

Hydro-flattening is a new term, first coined in the USGS Lidar Base Specification Version 1.0. It conveys the need of users to have a specific type of functional surface. Hydro-flattening of DEMs is accomplished predominantly through the use of breaklines, and this method is considered standard. Although other techniques may exist to achieve similar results, this section assumes the use of breaklines. The SOM does not require the use of any specific technique.

The Digital Elevation Model Technologies and Applications: The DEM User's Manual, 2nd Edition (Maune, 2007) provides the following definitions related to the adjustment of DEM surfaces for hydrologic analyses.

- *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 spurious sinks or pits. The only sinks that are retained are the real ones on the landscape. Whereas hydrologically-enforced is relevant to drainage features that are generally 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/links among basins/catchments can be known for large areas. This term is specifically used when describing Elevation Derivatives for National Applications (EDNA), the dataset of NED derivatives made specifically for hydrologic modeling purposes.

- *Hydrologically-Enforced (Hydro-Enforced)* Processing of mapped water bodies so that lakes and reservoirs are level and so that streams 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 would be 3-D 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. See also the definition for hydrologically conditioned that has a slightly different meaning.

Whereas these are important and useful modifications, they result in surfaces that differ substantially from a traditional DEM. A hydro-conditioned surface has had its sinks filled and may have had its water-bodies flattened. This is necessary for correct flow modeling within and across large drainage basins. Hydro-enforcement extends this conditioning by requiring water bodies be leveled and streams flattened with the appropriate downhill gradient, and also by cutting through road crossings over streams (culvert locations) to allow a continuous flow path for water within the drainage. These treatments result in a surface on which water behaves as it physically does in the real world, and they are invaluable for specific types of hydraulic and hydrologic (H&H) modeling activities. Neither of these treatments is typical of a traditional DEM surface.

A traditional DEM, on the other hand, attempts to represent the ground surface more the way a bird, or person in an airplane, sees it. On this surface, natural depressions exist, and roadways create apparent sinks because the roadway is depicted continuously without regard to the culvert beneath, making it an apparent dam. Bridges, it should be noted, are removed in most all types of DEMs because they are man-made, above-ground structures that have been added to the landscape.

Note: DEMs developed solely for orthophoto production may include bridges, as their presence can prevent the smearing of structures and reduce the amount of post-production correction of the final orthophoto. These are special use DEMs and are not relevant to this discussion.

For years, raster DEMs have been created from a digital terrain model (DTM) of masspoints and breaklines, which in turn were created through photogrammetric compilation from stereo imagery. Photogrammetric DTMs inherently contain breaklines defining the edges of water bodies, coastlines, single-line streams, and double-line streams and rivers, as well as numerous other surface features.

Lidar technology, however, does not inherently collect the breaklines necessary to produce traditional DEMs. Breaklines have to be developed separately through a variety of techniques, and either used with the lidar points in the generation of the DEM, or applied as a correction to DEMs generated without breaklines.

Supplemental Information

USGS Lidar Base Specification Version 1.0:
http://pubs.usgs.gov/tm/11b4/TM11-B4.pdf

Final Report; National Enhanced Elevation Assessment:
http://www.dewberry.com/Consultants/GeospatialMapping/FinalReport-NationalEnhancedElevationAssessment

USGS National Elevation Dataset (NED) Web site:
http://ned.usgs.gov/

National Digital Elevation Program Guidelines for Digital Elevation Data
http://www.ndep.gov/NDEP_Elevation_Guidelines_Ver1_10May2004.pdf

ASPRS LAS Specification
http://asprs.org/Committee-General/LASer-LAS-File-Format-Exchange-Activities.html

USGS Center for Lidar Information Coordination and Knowledge (CLICK) Web site:
http://lidar.cr.usgs.gov/

MP-Metadata Parser:
http://geology.usgs.gov/tools/metadata/

National Institute of Standards and Technology (NIST) Percentile Information:
http://itl.nist.gov/div898/handbook/prc/section2/prc252.htm