Specifications for Digital Elevation Models for the Province of British Columbia

Version 3.0

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Victoria, BC

GeoBC

BRITISH COLUMBIA

Ministry of
Land, Water and
Resource Stewardship

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Record Of Amendments

Version	Revised by	Revision Description	Approved by	Date
2.1	Isabelle Paquin Brett Edwards Robert Prins		Harald Steiner, P.Eng	21-Apr-2016
2.2	Brett Edwards	Naming convention	Robert Prins	7-May-2017
2.3	Brett Edwards	Breakline deliverables revision	Robert Prins	30-Apr-2018
2.4	Jordan Godau		Robert Prins	30-Apr-2019
2.5	Samantha Grant Jordan Godau	Minor updates throughout. Special Attention paid to section 8.0	Robert Prins	15-Apr-2020
3.0	Samantha Grant Spencer Floyd Kaitlyn McLaren Natalie Jackson	Vertical datum, compression, breakline requirement updates, overall edits for clarity	Brett Edwards	04-May-2022

1.0 Introduction

The main goal of this document is to provide geospatial data suppliers with common standards and clear requirements to produce Digital Elevation Models (DEMs), with the objective of obtaining consistent, high quality DEM deliverables to the B.C. Provincial Government.

To these specifications, the word “shall” indicates a mandatory requirement and “should”, indicates a desirable requirement. These Digital Elevation Model Specifications supersede all previous GeoBC Digital Elevation Model Specifications.

The term “Branch” when used herein shall mean GeoBC of the Ministry of Land, Water and Resource Stewardship in the Province of British Columbia. The Branch shall be the final authority on acceptance or rejection of submitted DEM results, products, and materials.

All DEM material, data and products delivered to the Branch shall meet or exceed the following specifications.

2.0 Purpose And Scope

This document does not define detailed requirements for the initial photogrammetry, Light Detection and Ranging (LiDAR) datasets, or any other source data, used to create the derived DEMs. Although a brief overview of the source data acquisition technology and some of the elements/practices affecting the accuracy and resolution requirements of the input data are described, the suppliers shall ensure that the complete requirements of the source data are met before deriving any elevation models.

The specifications for the source datasets shall be based on the document ASPRS Positional Accuracy Standards for Digital Geospatial Data [1] and suppliers shall include the required datasets and information related to source data in the deliverables, as enumerated in the project specific requirements.

The specifications in this document shall be applicable to the attributes and deliverables related to DEMs, including the final resolution and accuracy of the models, the descriptive metadata, spatial reference system information and relevant reports to be delivered (see Section 7.0).

3.0 Digital Data Model Description

This section includes brief descriptions of terrain and elevation models applicable to these specifications, as defined by the Branch. Although there are sources offering different definitions, the nomenclature presented in this section shall be used when describing and/or reporting deliverables to the Branch.

Regarding these specifications, the term gridded DEM is used instead of raster DEM.

3.1 Digital Terrain Model (DTM)

A Digital Terrain Model (DTM) is a computer representation of terrain stored in a digital data file as a set of discrete points with 3D coordinates; Easting (x), Northing (y) and elevation (z).

It is often a derived product of mass points which include all the features of the surface (see Figure 1 and Figure 2) while the DTM represents the bare ground surface of the terrain, excluding vegetation and built-up features.

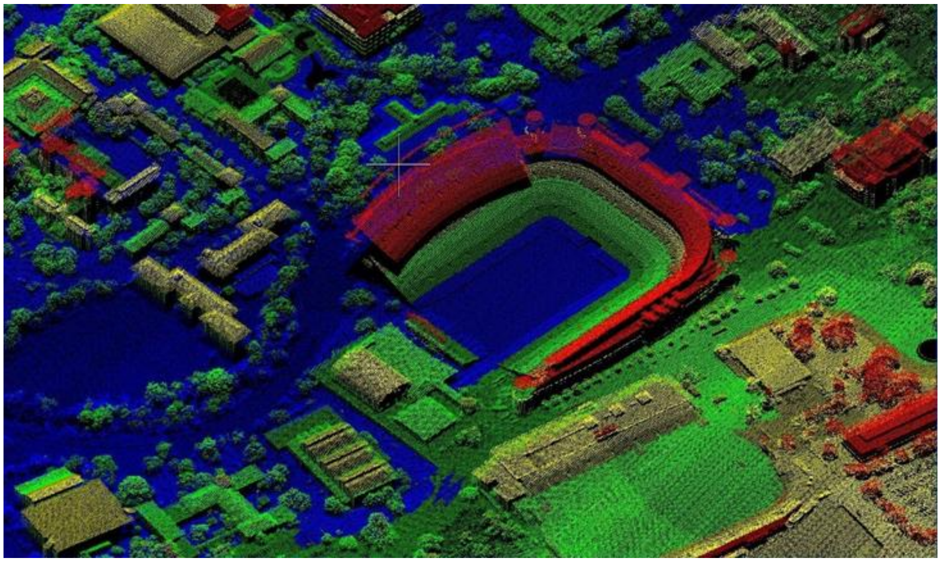

Figure 1: Example of a point cloud DSM, from LiDAR

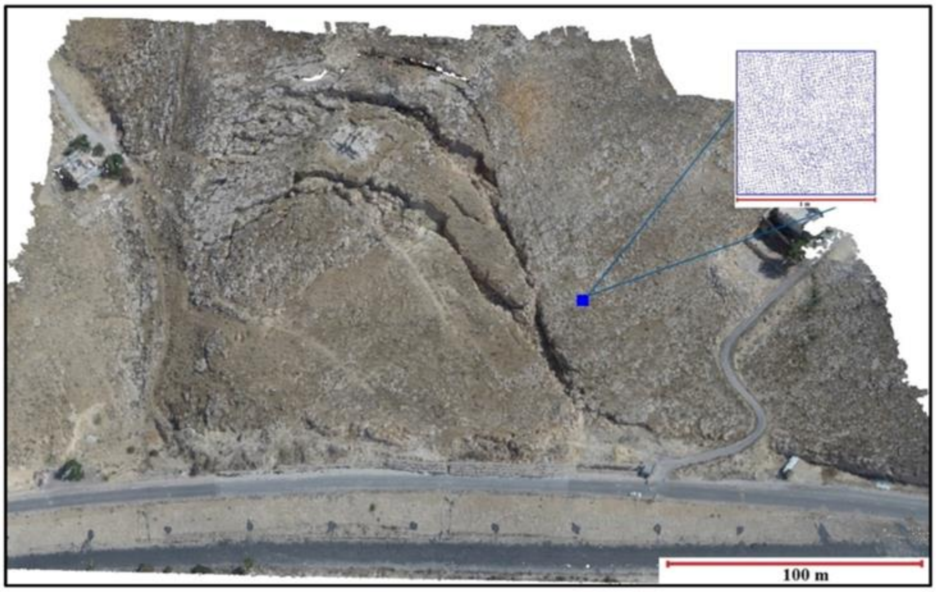

Figure 2: Example of a point cloud DSM, generated using Semi-Global Matching (SGM)

A DTM is not a surface model, since its component elements are irregularly or randomly spaced mass points and are not continuous, a surface must be derived from the DTM to create a Digital Elevation Model (DEM). This involves two important concepts that need to be briefly mentioned in the next section describing DEMs; tessellation and interpolation. In addition to mass points, the DTM data structure often incorporates breaklines to retain abrupt linear features and to assist in hydro-flattening (see Appendix A: Hydrologic Treatments) in the derived elevation model, as needed.

3.2 Digital Elevation Model (DEM)

A DEM is a digital representation of continuous elevation values over a topographic functional surface either from a regular, or irregular, array of z-values. Although there are other means of representing a digital surface from DTM points, the specifications in this document apply to two commonly used types of DEMs; gridded DEM and vector-based Triangulated Irregular Networks (TIN) DEM.

Note that a gridded DEM can also be derived from a vector-based TIN, when the loss of resolution is not an issue, and/or when the size of the models is problematic. Furthermore, both types of DEMs can be used to derive additional products such as contour lines, aspect raster, or hillshaded raster (Figure 3). Those products derived from DEMs are not covered by these requirements.

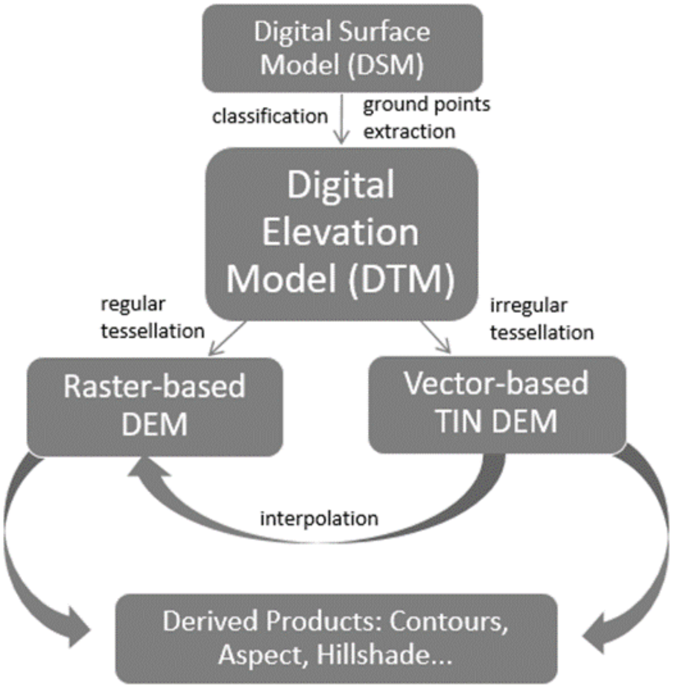

Figure 3: Typical data flow from DSM to derived products

The term DEM, when used herein, shall be applicable to both gridded DEM and vector-based TIN.

3.3 Gridded DEM

The Branch makes the following distinction between a raster and a lattice, as applicable to these requirements used to produce DEMs.

A raster shall be defined as a set of regularly spaced, continuous cells with bare-earth elevation values attached to the center of each cell, where the value for a cell is assumed to be valid for the whole cell area. Raster centroid coordinates are contained in the arrangement of the matrix. See Figure 4 for an illustration of the step effect caused by raster cells.

A lattice shall refer to the values at the intersection (nodes) of the regularly spaced lines. For example, discrete elevation measurements that occur at regular intervals in x and y relative to a common origin. The resolution of the grid corresponds to the distance between to neighbour nodes. See Figure 4 for an illustration of the lattice mesh. A lattice differs from a raster 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 raster cell.

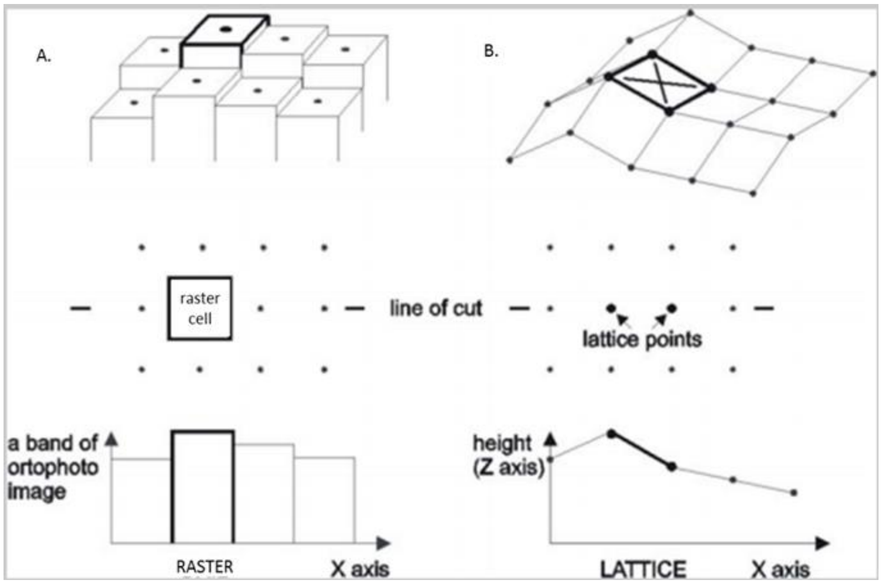

Figure 4: Differences between a raster and a lattice

Bare-earth gridded DEMs are free from vegetation, buildings, bridges, and other built-up features. Unless otherwise specified in the project requirements, roads at ground level shall be kept by default and classified as ground [2].

3.4 TIN DEM

For irregular tessellations, the surface is also partitioned into mutually disjointed cells, but those cells vary in size and shape, so they can adapt to the surface they represent.

The Triangulated Irregular Network (TIN) is one of the most frequently used vector-based representations for the storage of surface model information, although it can be considered a hybrid between tessellations and vector representations (see Figure 5). A TIN DEM is a vector data structure that partitions geographic space into contiguous, non-overlapping triangles computed from irregularly spaced points with x/y coordinates and z-values. In other words, an irregular tessellation of triangles can be made from the mass points of a source dataset, to create planes representing a surface. The most common method of generating triangles for a TIN is Delaunay triangulation. It is a proximal method that satisfies the requirements that a circle drawn through the three nodes of a triangle will contain no other node and that the triangles must be as equilateral as possible. This ensures that any point on the surface is a close as possible to a node while reducing the problems created by skinny triangles.

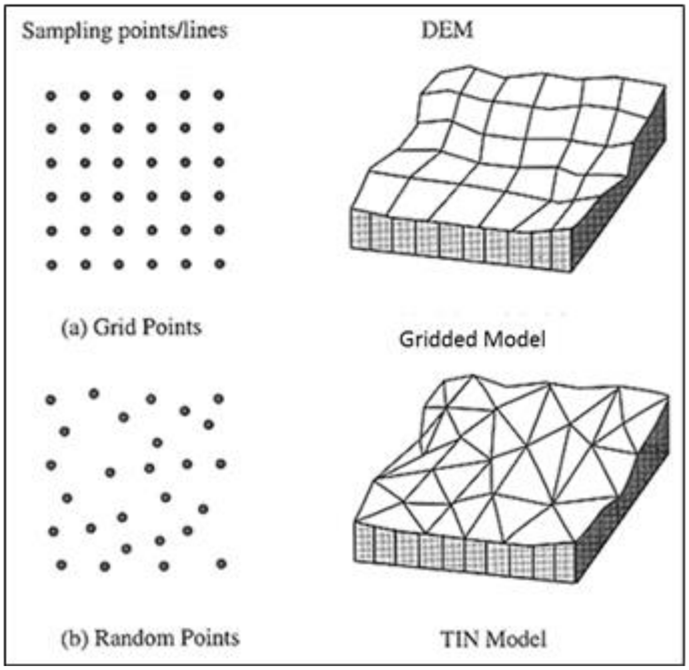

Figure 5: Gridded DEM and TIN

3.5 Interpolation Methods

Interpolation is a procedure used to predict the values of cells at locations lacking sampled points and is based on the principles of spatial autocorrelation, which assumes that nearby points are more similar when compared to farther ones. As field sampling points are observed at discrete intervals, a DEM shall be built to allow the interpolation of elevation values at arbitrary points of interest to represent the three dimensions; z = f(x,y), depending on the chosen model type.

The triangular planes of a TIN, for example, indicate elevation values that are interpolated from the points used to create them. A disadvantage of this interpolation method is that the surfaces are not smooth and may show a jagged appearance while interpolations methods used to generate a gridded DEMs are usually more forgiving in terms of noise, giving smoother surfaces.

Even though several interpolation methods can be used to derive a gridded DEM from a DTM or a TIN, the bicubic interpolation method shall be used by default, unless otherwise specified in the project requirements. Interpolation from contour lines shall not be used to derive DEMs.

3.6 Comparison of DEM types

Depending on the project specific requirements, the supplier shall provide either gridded DEMs or vector-based TINs, or both. Some factors that are considered in the delivery method of either gridded DEMs or vector-based TINs include: the intended use of the model, the final resolution needed, financial and storage constraints, and software available for viewing and editing the models. Table 1 lists some examples of advantages and disadvantages for each model type.

Table 1: Comparison of Model Types

Criteria	Gridded DEM	Vector-based TIN (derived from LiDAR or SGM)
Preservation of exact location of each ground point possible	No	Yes
Preservation of precise location of narrow features	No	Yes
Storage: files sizes and format	Small, efficient storage, widely used formats	Larger files size, limited choice of formats
Speed of retrieval and processing data	Quick retrieval and processing times	Slower retrieval and processing times
Smooth and more natural appearance of derived features	Yes, better at handling noise	More jagged appearance, need more manual editing
Various resolutions to reflect areas of different complexity of relief	No	Yes
Ease of creation, use, rendering, interpretation	Well-known, relatively easy	Relatively new technologies
Degradation by interpolation	Yes	Less (happens mostly during ground classification)
Level of effort for visual inspection and manual control of the model	Less	More
Software available for creation and analysis	Wide choice, relatively inexpensive	Choice more restrained, often expensive

3.7 Elevation Types

Two main elevation types or heights are explained below. Unless otherwise specified in the project requirements, the elevation of any point shall be represented as orthometric height.

Orthometric height is the height above the geoid as measured along the plumbline between the geoid and a point on the Earth's surface, taken positive upward from the geoid (see Figure 9).

Ellipsoidal height is the height above or below the reference ellipsoid, i.e., the distance between a point on the Earth's surface and the ellipsoidal surface, as measured along the normal (perpendicular) to the ellipsoid at the point and taken positive upward from the ellipsoid.

This is the height obtained from GPS surveys (including technologies which utilize airborne Global Positioning System (GPS)), prior to corrections for the undulation of the geoid. Ellipsoidal heights are independent of the local direction of gravity [3].

Figure 6 illustrates the differences between the height types, where:

N = geoid separation (deviation between the Geoid and a reference ellipsoid)

H = Orthometric Height

h = Ellipsoidal Height

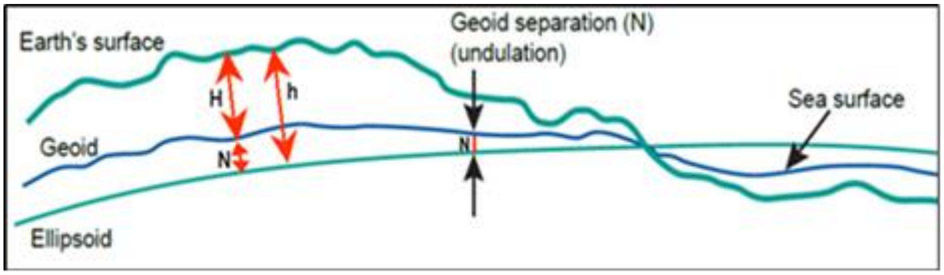

Figure 6: Diagram illustrating different elevation/height types

4.0 Source Data Requirements

When delivering DEMs, the data suppliers shall provide reports indicating that the absolute accuracy and precision of the source data meets or exceeds the requirements for the derived DEM since interpolation and/or smoothing will, amongst other factors, negatively affect the absolute accuracy of the final product.

Data sources and processing methods for generating DEMs have evolved dramatically over the last few decades. Currently, there are three major sources of elevation data: ground survey techniques, digitizing of topographic maps, and remote sensing. To these specifications, the processing and interpretation of images and data acquired from airborne sensors (remote sensing) shall be considered the main source of elevation data used to derive DEMs.

4.1 Stereo Matching

Aerial photography is a passive remote sensing technique which measures energy that is naturally available. The sun's energy is the source of illumination for aerial photogrammetric acquisition and is either reflected, as it is for visible wavelengths, or absorbed and then re-emitted as heat, as it is for thermal infrared wavelengths. The mapping from vertical aerial photographs (i.e., photogrammetry), is the technology of obtaining reliable information about physical objects and the environment through the processes of recording, measuring, and interpreting photographic images.

Stereo photogrammetry is a technology relevant to this document and involves estimating the x, y, and z coordinates of points employing measurements made from two or more aerial photographic images taken from different positions, using stereo matching methods. The resulting point cloud can then be used to derive a DEM.

Stereo matching is used to find corresponding pixels in a pair of images, which allows 3D reconstruction by spatial resection, using the known inherent and external orientation parameters of the camera(s). Unfortunately, the problem is ill-posed since images are locally very ambiguous. Many techniques have been proposed in photogrammetry, however, all of them are suboptimal.

Semi-Global Matching (SGM) is a method developed by Dr. H. Hirschmüller [4, 5, 6, 7] that offers a good trade-off between accuracy and runtime and is well suited for accurate 3D reconstruction from stereo images. It is the method that shall be used by default for generating 3D point clouds from 2D stereo imagery. See Section 4.3 for a general comparison between mass point clouds generated by SGM and LiDAR [7].

When stereo photogrammetry is the source of the derived DEM, suppliers shall ensure that the horizontal accuracy and Ground Sample Distance (GSD) of the images used, as well as the point spacing and density of the final mass-points DTM exceed the requirements for the derived DEM (see Section 6.0 and Section 7.0). All systematic errors and bias shall be addressed and corrected before deriving DEMs. Furthermore, no points shall be added to the mass points using linear interpolation.

4.2 LiDAR

Light Detection and Ranging (LiDAR) is an active remote sensing technology that emits pulses of laser light to strike the surface of the earth and measure the time of each pulse return to derive an accurate 3D coordinate. LiDAR systems are complex, multi-sensor systems consisting of at least three sensors; a laser rangefinder, a Global Navigation Satellite System (GNSS), and a high-end Inertial Navigation System (INS). Proper system calibration, including individual sensor calibration, inter-sensor calibration, and time synchronization between system components are essential to achieve the required LiDAR points accuracy.

The general production steps are shown in Figure 7, each affecting the final accuracy of the derived products. Consult the most recent version of the GeoBC Specifications for LiDAR [2] for more information on the requirements applicable to LiDAR source data.

Figure 7: General production steps for LiDAR for DTM generation

When LiDAR is the source of the derived DEM, suppliers shall ensure that the horizontal accuracy as well as the point spacing and density of the final mass points exceed the requirements for the derived DEM (see Section 6.0 and Section 7.0). All systematic errors and bias shall be addressed and corrected before deriving DEMs. Furthermore, no points shall be added to the mass points measured using linear interpolation.

4.3 SGM versus LiDAR for DSMs Generation

The comparison between LiDAR and SGM as a generation method for DSMs (before ground points extraction) is briefly addressed in Table 2.

Table 2. Comparison Between LiDAR Derived DSMs and SGM Derived DSMs

Criteria	DSMs acquired with LiDAR	DSMs generated using SGM
Vegetation penetration	High	Depending on vegetation type and density
Vertical/Horizontal accuracy	High/High	Low to Intermediate/High
Hardware/Software requirements	High	Medium
Cost	High	Low to Intermediate
Object reconstruction capabilities	Not possible unless planar features	High
Probability of geospatial referencing errors	Low	High
Capable of direct classification	Low - unless supported by imagery	Very High
Turnaround time	Slow to Medium	Fast turnaround time

4.4 Other Data Sources

Some active sensor systems make use of other parts of the electromagnetic spectrum and can be used to generate DEMs.

One example is radar, which uses the reflection of radio waves or microwaves on features instead of ultraviolet, visible, or near infrared light from lasers. Radar sensors can be mounted on either space-borne (satellites) or airborne (aircraft) platforms.

Synthetic Aperture Radar (SAR) is a form of radar in which sophisticated processing of radar is used to produce a very narrow effective beam. This type of sensor can be used to form images of relatively immobile targets; moving targets can be blurred or displaced in the formed images. SAR, being a form of active remote sensing, is therefore independent of natural illumination and images can be collected at night. Furthermore, since radar uses electromagnetic radiation at microwave frequencies and the atmospheric absorption at typical radar wavelengths is very low, observations are not impeded by cloud cover.

Radargrammetry [8] can be used to calculate the 3D coordinates for corresponding points on a stereo pair of SAR images. This technique is usually employed with stereoscopic pairs acquired from the same side but with different incidence angles. Another approach to extract elevation information from the SAR images is Interferometric Synthetic Aperture Radar (InSAR). InSAR makes use of two complex SAR images, which are acquired from slightly different perspectives, and pixel-by-pixel phase differences are converted into elevation differences of the terrain, using differences in the phase of the waves returning to the satellite or aircraft.

5.0 Accuracy Requirements

The absolute vertical accuracy and the horizontal accuracy of the DEM shall be assessed and reported in accordance with the following sections, based on the ASPRS Positional Accuracy Standards for Digital Geospatial Data [1]. To align with ASPRS accuracy standards, two broad land cover types shall be defined for accuracy; non-vegetated and vegetated, each with a corresponding accuracy indicator: non-vegetated vertical accuracy (NVA) and vegetated vertical accuracy (VVA).

5.1 Non-vegetated Vertical Accuracy (NVA)

Non-vegetated vertical accuracy relates to the measures done on the derived DEM compared to verification points. Orthometric heights shall be used for all accuracy reporting and measurements (see Section 3.7).

NVA is an estimate of the derived DEM vertical accuracy at the 95% confidence level, in non-vegetated, open terrain, and shall comply with the NVA requirements listed in Table 3, according to the quality level (QL) of the project (see Section 6.1).

NVA is calculated by multiplying the $RMSE_z$ by 1.96 [1].

$$\textbf{NVA} = RMSE_z \times 1.96 \text{ (at 95\% Confidence Level)}$$

Listed below are most of the non-vegetated cover types that may apply to a typical project. The Branch reserves the right to include or exclude specific cover types in the project requirements.

- Non-vegetated land cover types may include but are not limited to clear or open terrain, bare-earth or asphalt, low grass, sand, rock, dirt, plowed fields, lawns, golf courses.

Only the NVA shall be used for production and testing of the input mass data points, as well as for the accuracy verification of the derived DEM.

5.2 Vegetated Vertical Accuracy (VVA)

Vegetated vertical accuracy points may be used as supplemental checkpoints. Suppliers shall contact the Branch prior to any data acquisition and/or use of this indicator if they have concerns about respecting the NVA in all areas of the project. VVA points are used as additional points to account for any discrepancies.

Vegetated vertical accuracy relates to measures that shall be done on the derived DEM compared to verification points. The orthometric height shall be used. VVA is an estimate of the derived DEM vertical accuracy, based on the 95th percentile, in vegetated terrain and shall comply with the VVA requirements listed in Table 3, according to the QL of the project. Since the source data points collected in vegetated terrain typically have the most errors due to noise and/or incorrect classification, they often entail the most time and effort to correct.

Many of the vegetated cover types that may apply to a typical project are listed below. The Branch reserves the right to include or exclude specific cover types in the project requirements.

- Vegetated land cover types may include, but are not limited to tall grass, weeds and crops, brush lands and short trees, forested areas fully covered by trees.

Specific methods for testing vertical accuracy on derived DEMs will depend on the technology used and project design. The data supplier is responsible for establishing appropriate methodologies, applicable to the technologies used, to verify that vertical accuracies meet or exceed the project requirements. Reporting of the accuracy testing is outlined in Section 7.0.

5.3 Horizontal Accuracy

Horizontal errors are more difficult than vertical error to assess in the final DEMs. This is mainly due to the bare-earth derived surface lacking well defined topographic features necessary for such tests, or because the resolution of the elevation data might be too coarse for precisely locating distinct surface features, depending on the model type and source data type used.

For these reasons, data producers shall report the measured horizontal accuracy of the source data.

5.3.1 Estimation of Horizontal Accuracy (RMSE_r) based on LiDAR

$$\boldsymbol{RMSE_r} = \sqrt{(\theta_{laser}\ AGL)^2 + \left(\sigma_{GNSS_{xy}}\right)^2 + \left(\sigma_{IMUrp}\ AGL\right)^2}$$

where:

$\boldsymbol{RMSEr}$ = Horizontal accuracy over flat terrain (metres) at 63% probability

$\boldsymbol{\theta_{laser}}$ = Laser beam divergence (milliradians)

$\boldsymbol{AGL}$ = Flying height above ground (metres)

$\boldsymbol{\sigma_{GNSS_{xy}}} \cong \mathrm{RMSE}_r$ = Average 2D positional accuracy of the GPS system (metres) at 63% probability

$\boldsymbol{\sigma_{IMUrp}}$ = Average angular accuracy of the drift corrected IMU in roll and pitch orientation (milliradians)

5.3.2 Photogrammetric Horizontal Accuracy ($RMSE_r$): Indirect Georeferencing

$$RMSE_r = \sigma_{XY_{AT}} = \sqrt{\left(\frac{\sigma_X\, AGL}{f}\right)^2 + \left(\frac{\sigma_Y\, AGL}{f}\right)^2}$$

where:

$RMSE_r$ = Horizontal accuracy over flat terrain (metres) at 63% probability

$\boldsymbol{AGL}$ = Flying height above ground (metres)

$\boldsymbol{\sigma_X}$ = Standard deviation of the image measurement in the X axis, from the Bundle Block Adjustment (metres)

$\boldsymbol{\sigma_Y}$ = Standard deviation of the image measurement in the Y axis, from the Bundle Block Adjustment (metres)

$\boldsymbol{f}$ = Focal length (metres)

5.3.3 Photogrammetric Horizontal Accuracy ($RMSE_r$): Direct Georeferencing

$$RMSE_r = \sigma_{XY_{GNSS/INS}} = \sqrt{\left(\sigma_{IMU_{rp}}\, AGL\right)^2 + \left(\frac{1}{3}\, GSD\right)^2}$$

where:

$RMSE_r$ = Horizontal DEM accuracy over flat terrain (metres) at 63% probability

$\boldsymbol{AGL}$ = Flying height above ground (metres)

$\boldsymbol{\sigma_{IMUrp}}$ = Average angular accuracy of the drift corrected IMU in roll and pitch orientation (radians)

$\boldsymbol{GSD}$ = Ground Sample Distance (metres)

6.0 Quality Assurance

This section outlines the quality assurance requirements that shall be met or exceeded by a data supplier.

6.1 Quality Levels

To keep the quality of a DEM at the highest level, DEMs shall be interpolated from source data of higher accuracy and point density than the final grid cell size or final point density of the DEMs being produced. Any technology can be used to generate the source data (subject to project requirements) if the designated quality level requirements are met (see Table 3).

The values listed in Table 3 are modified from the ASPRS [1] standards with the fields defined as follows:

Table 3. Requirements Per Quality Level (QL)

Quality Level	Accuracy Class	NVA required	VVA required	DEM Grid Size (m)	TIN Point Density (pts/m^2)
QL1	5.0 cm	± 9.80 cm	± 15 cm	≤ 0.50	> 8
QL2	10 cm	± 19.60 cm	± 30 cm	1.0	> 2
QL3	20 cm	± 39.20 cm	± 60 cm	2.0	> 0.5
QL4	1.0 m	± 1.96 m	± 3 m	5.0	> 0.05
QL5	3.0 m	± 6.53 m	± 10 m	≥ 10	> 0.01

- Quality Level (QL): For every project, the Branch shall specify which of the five QL requirements the supplier shall adhere to concerning the derived DEMs. QL1 requires the highest accuracy and resolution requirements, while QL5 requires the lowest.
- Accuracy Class: Required maximum non-vegetated elevation Root-Mean-Squared Error ($RMSE_z$) reported for the input data, at 68% Confidence Level.
- NVA Required: Non-vegetated vertical accuracy relating to the measures done on the derived DEM versus verification points, at 95% Confidence Level (see Section 5.1).
- VVA Required: Vegetated vertical accuracy relating to the measures done on the derived DEM vs verification points, at 95th Percentile (see Section 5.2).
- DEM Grid Size: Maximum cell size if the DEM is interpolated to a grid.
- TIN Point Density: Minimum points density if the DEM is a TIN.

6.2 Data Formatting

The following requirements shall be met and adhered to for the delivery of DEMs relating to header information, metadata, file naming and file formatting. File naming shall adhere to the GeoBC Digital Data Naming Convention Specification [9]. DEMs delivered that do not adhere to the below requirements shall be cause for rejection of the deliverables.

- Void areas shall be coded using a unique “NODATA” value of -32767
- Pixel size for DEM deliverables shall be whole number float values (e.g., 1.00), trailing nonzero decimal values will not be accepted (e.g., 1.0000001121).
- Origin and corner values for DEM deliverables shall be positioned on whole number float values (e.g., 5455946.00), such that they are evenly divisible by the pixel size of the given raster (i.e., the origin or corner values divided by the pixel size will always yield a remainder of zero). This can be adhered to by utilizing the appropriate tiling grids found on the Branch FTP site: **ftp:\\ftp.geobc.gove.ca\sections\outgoing\dis\Specifications\Tiling_Grids**.
- DEMs shall be delivered as GeoTIFF in compliance with GeoTIFF Specification and Revision 1.1 [10].
- GeoTIFF DEMs shall be compressed using LZW (Lempel-Ziv-Welch) lossless compression algorithm.
- If multiple isolated project areas[1] fall within a BCGS map tile, the DEM for all project areas within the tile shall be delivered as a single file.
- DEMs shall have a 100-metre buffer outside the AOI as well as between tiles during production (the processing limit). Adjacent tiles shall have overlap during, and post-production.
- The DEMs shall be clipped and include a 50-metre buffer outside the AOI(s) when delivered. Note that a buffer may cause data to extend to an adjacent BCGS tile, which shall also be included in a project delivery.
- Correct file naming convention shall be used as outlined in the latest version of the GeoBC Naming Conventions Specification.
- The source data files (and breaklines shapefiles if they were used) with a description of the processing steps and interpolation methods used, when applicable, shall be delivered with the derived DEMs.

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[1] The Branch defines an isolated project area as a project area that is spatially separated from other project areas such that collected source data does not overlap. This spatial separation usually occurs when project areas are not continuous (made up of multiple, separate polygons) or when there are natural features (e.g., large water bodies) preventing source data from overlapping.

6.3 DEM Quality Requirements

DEM surface quality shall adhere to the following requirements, and DEMs that are found to contain any of the below errors will be cause for rejection of the entire DEM deliverable.

- A quilted appearance in the overall DEM surface, whether it is caused by differences in processing quality or character among tiles, swaths, lifts, or other non-natural divisions.
- DEM surfaces between tiles, or within a tile shall have no edge artifacts or mismatch.
- Low Confidence Areas [1] shall not be acceptable as part of the DEMs.
- Data voids/holes remaining in the surface
- Where hydro-flattening is required, any areas that do not adhere to the requirements listed in Appendix A: Hydrologic Treatments.

6.4 Metadata and GeoTIFF Headers

Metadata shall be included with the deliverable on the order of at least one Extensible Markup Language (XML) file per project, conforming to the Federal Geographic Data Committee [11] standards. More than one file shall be included if there are distinct attribute differences within data subsets. At a minimum, it shall contain information pertaining to the coordinate system including Ellipsoid, Horizontal/Vertical Datum, Coordinate System and Units.

GeoTIFF headers shall include the Coordinate Reference System (CRS) in Well Known Text (WKT) with horizontal and vertical datum, and projection information. Refer to Section 6.2 for other formatting requirements. An example of proper GeoTIFF header information is in Appendix D: Example GeoTIFF Header.

7.0 Project Deliverables and Supplementary Reports

This section outlines the expected reporting and metadata deliverables to accompany a DEM project, unless otherwise specified in a contract.

7.1 DEM Metadata Report

A DEM metadata report shall be completed by the data supplier and list the specific project requirements that were achieved (see

Appendix B: DEM Metadata Report), delivered in PDF (.pdf) format.

7.2 Accuracy Reporting

Accuracy reports shall be delivered for each dataset used as source data and for derived DEMs, using the blank forms in Appendix C: Accuracy Reporting. Examples with five control or verification points can be seen in Table 4 and Table 5. Definitions and equations for the terms used in the tables can be found in Appendix C: Accuracy Reporting and in the Glossary of Terms. Although the tables show only 5 control/verification points, for LiDAR-derived DEMs, the number of control points shall adhere to the requirements in the Specifications for Airborne LiDAR for the Province of British Columbia [2]. For all other products, the number of control points shall adhere to the contract.

Table 4. Example of an Accuracy Report for Source Data

Point ID	**Measured Values (metres)**			**Survey Check Point Values (metres)**			**Residuals (errors) (metres)**		
	Easting (x)	**Northing (y)**	**Elevation (z)**	**Easting (x)**	**Northing (y)**	**Elevation (z)**	**Δx Easting**	**Δy Northing**	**Δz Elevation**
GCP1	359584.394	5142449.936	477.134	359584.530	5142450.001	477.202	-0.136	-0.065	-0.068
GCP2	359872.198	5147939.188	412.415	359872.291	5147939.288	412.402	-0.093	-0.100	0.013
GCP3	395893.099	5136979.828	487.289	395893.071	5136979.896	487.192	0.028	-0.068	0.097
GCP4	359927.197	5151084.133	393.591	359927.262	5151083.984	393.694	-0.065	0.149	-0.103
GCP5	372737.077	5151676.001	451.313	372736.943	5151675.882	451.226	0.134	0.119	0.087
Number of check points							5	5	5
Mean Error							-0.026	0.007	0.005
Standard Deviation							0.108	0.117	0.090
Root-Mean-Square Error RMSE, 1dRMSE at 68% Confidence Level							0.100	0.105	0.080
Radial Horizontal Accuracy RMSE$_r$, 1dRMSE$_r$ at 63% Confidence Level							0.145		
Non-vegetated Vertical Accuracy (NVA) at 95% Confidence Level							0.158		
Vegetated Vertical Accuracy (VVA) at 95th Percentile							0.240		

Table 5. Example of an Accuracy Report for DEM products

Point ID	Measured Values	Survey Check Point Values	Residuals (errors) (metres)
	Elevation (x)	**Elevation (z)**	**Δz Elevation**
VP1	477.13	477.20	-0.071
VP2	412.41	412.40	0.010
VP3	487.29	487.19	0.102
VP4	393.59	393.69	-0.100
VP5	451.31	451.22	0.087
Number of Checkpoints			5
Mean Error			0.006
Standard Deviation			0.091
Root-Mean-Square Error RMSE, 1dRMSE at 68% Confidence Level			0.081
Non-vegetated Vertical Accuracy (NVA) at 95% Confidence Level			0.159
Vegetated Vertical Accuracy (VVA) at 95th Percentile			0.243

7.3 Breaklines

Breaklines are linear data structures that represent a distinct or abrupt change in the terrain. They contain a series of vertices with associated z-values. When used with a DTM, breaklines can be forced as edges in a TIN model and more precisely delineate linear features whose shape and location would otherwise be lost or to delimitate water bodies.

Breakline deliverables shall conform to the following procedures and specifications:

- Breaklines shall be developed to the 100-metre processing limit (see Section 6.2).
- Breaklines shall be delivered in ESRI shapefile format as a closed PolygonZ or PolylineZ features, as appropriate to the type of feature represented in Appendix A: Hydrologic Treatments (i.e., inland ponds and lakes, tidal water bodies, etc.).
- Breaklines that are delivered as individual polyline segments, or unclosed polygons shall be cause for rejection of the breakline deliverables.
- Where breaklines are at or near the edge of an AOI, the breaklines shall be closed by the AOI boundary, unless a waterbody extends beyond the AOI where the breaklines shall be closed to the extent of the processing limit (see Figure 8).
- Delivered in the same coordinate reference system (horizontal and vertical) and units as the DEM.
- Each shapefile shall include a correct and properly formatted .prj file.
- Delivered breaklines shall be sufficient to effectively re-create the delivered DEM using the source mass points and breaklines without substantial editing.

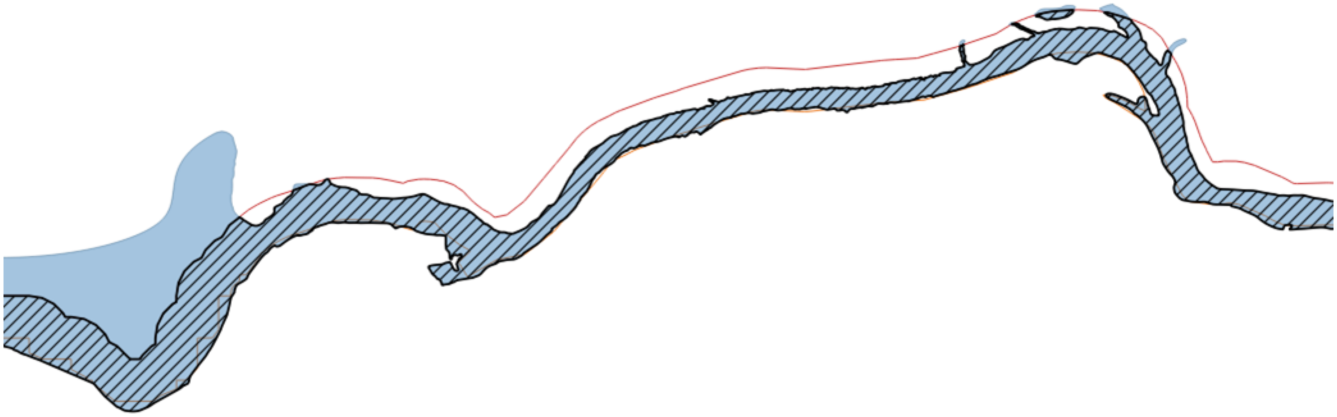

Figure 8: Blue outline is water, black hashmark polygon indicates where breaklines are expected to extend; either to the edge of the processing boundary (thin red line), or the edge of the waterbody, if the waterbody's edge is inside the processing limit (100m buffer)

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Appendix A: Hydrologic Treatments

Hydro-flattening is the default treatment for water bodies and pertains only to the creation of derived DEMs, particularly vector-based TIN derived from mass points. Hydro-flattening of DEMs is predominantly accomplished using breaklines, and this method is considered standard. The goal is not to provide accurately mapped, geographically corrected water surface elevations but to produce topographic DEMs that with respect to water surfaces, resemble DEMs derived from traditional photogrammetric methods and free of most unnatural triangulation effects [12].

Figure 9 shows an example of the effects adding breaklines can have on the aspect of the TIN. The figure on the left identifies a DEM surface without hydro-flattening applied, while the right is hydro-flattened using the orange coloured breaklines.

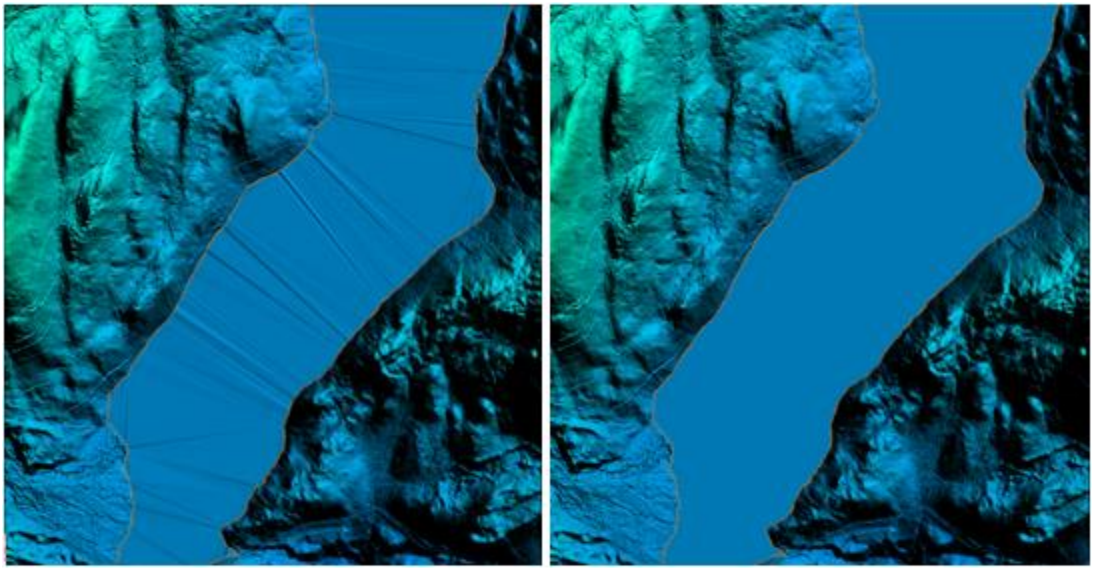

Figure 9: Example of breaklines used for hydro-flattening

The requirements for hydro-flattening are listed below, modified from the USGS 1-meter Digital Elevation Model Specification [13] hydro-flattening requirements. These requirements also define the minimum features for which breaklines shall be collected and delivered. Delivered digital surface models (DSMs) shall be hydro-flattened so waterbodies match that of the DEM in extents and elevation.

The following sections are modified from the USGS 1-meter Digital Elevation Model Specification [13] hydro-flattening requirements.

Inland Ponds and Lakes

- Water bodies of 8,000m^2 or greater surface area at the time of collection shall be flattened.
- Flattened water bodies shall present a flat and level water surface (a single elevation for every bank vertex defining the water body's perimeter).
- The entire water surface edge shall 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, inlets, and fjords, whose water surface elevations decrease with downstream travel) shall be treated as inland streams or rivers.

Inland Streams and Rivers

- Streams and rivers of an average 30m width shall be flattened and shall not be broken into multiple segments.
- 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.
- Stream channels shall break at culvert locations leaving the roadway over the culvert intact.
- Bridges in all their forms shall be removed from the DEM/TIN and streams shall be continuous at bridge locations.
- When the identification of a structure as a bridge or culvert cannot be made definitively, the feature shall be regarded as a culvert.

Non-tidal Boundary Water Bodies

- Boundary waters, regardless of size, shall be represented only as an edge or edges within the project; collection does not include the opposite shore.
- The entire water surface edge shall be at or below the immediately surrounding terrain.
- The water surface elevation will be consistent throughout the project.

- The water surface shall be flat and level, as appropriate for the type of water body (level for lakes, a gradient for streams and rivers).
- Any unusual changes in the water surface elevation during acquisition (such as increased upstream dam discharge) shall be documented in the project metadata.

Tidal Water Bodies

Any tidal water body is any water body that is affected by tidal variations (i.e., 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. As it is the intent for the DEM to represent as much ground as the collected data permits, ground points shall not 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 be completed at low tide to maximize collection and so tidal differences at the land-water interface are minimized.

In addition to meeting the requirements for inland water bodies listed in the sections above, as appropriate, the treatment of tidal water bodies shall also meet the following requirements:

- Vertical discontinuities within a water body resulting from tidal variations during the collection are considered normal and shall be retained in the DEM.
- Horizontal discontinuities along the shoreline of a water body resulting from tidal variations during the collection are considered normal and shall be retained in the final DEM.
- Long tidal water bodies that also exhibit downhill flow (such as a fjord) can present unusual challenges; data vendors are to exercise their best professional judgment in determining the appropriate approach solution to meet the overall goal of hydro-flattening as described in this section.
- For projects located in coastal areas, a project contract may impose additional requirements for tidal coordination.

Islands

- Permanent islands 4,000m^2 or larger shall be delineated within all water bodies. Project specific requirements shall override this specification.

Single-Line Streams or Additional Breaklines

Specific projects may require collection and integration of breaklines representing single-line streams, rivers, culverts, and other features.

If collected and incorporated into the DEM, the requirements are:

- All vertices along single-line stream breaklines shall be at or below the immediately surrounding terrain.
- Breaklines representing single-line streams, culverts, or other hydrographic features shall not be used to introduce hydrologic flow paths through road crossings (culverts), dams, or other similar topographic features.

Other Hydrological Treatments

The following definitions relate to the adjustment of DEM surfaces for other hydrologic analyses [14]. These hydrological treatments would be project specific and the final requirements shall be determined by the Branch.

- **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 false 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.
- **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) 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 utilize 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 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.

Appendix B: DEM Metadata Report

DEM Metadata Report	
Owner:	Ministry of Land, Water, and Resource Stewardship (GeoBC Branch)
Project Name & Contract Number:	
Date of data Submission:	
Project Location:	

	Parameter	**Value**
Data Formatting	*Quality Level:*	
	Grid Cell Size (resolution, metres):	
	Source Data Point Density (points/m^2):	
	File Compression Algorithm:	
	Derived DEM File Format (extension):	
	NoData Value:	
	Whole Number Float Origin and Corner Coordinates (Yes/No):	
	Clipped Buffer Applied (metres):	

	Parameter	**Value**
Accuracy	*Non-vegetated vertical accuracy (NVA):*	
	Number of Control Points:	
	Vegetated vertical accuracy (VVA):	
	Number of Control Points:	

	Model Type	**Model Components**	**Surface Treatments**
Model and Source Data Information	☐ *Gridded DEM*	☐ *Bare-Earth*	☐ *Breaklines used for Model*
	☐ *TIN*	☐ *Hydro-Flattened*	☐ *DTM Points Thinned (factor:__)*
	☐ *Source DTM*	☐ *Bridges Excluded*	☐ *Buildings Flattened*
	☐ *Other: ___________________*	☐ *Roads Classified as Ground*	☐ *Other: ____________________*
		☐ *Other: _______________*	
	Source Data Technology	**Source DTM Type**	**Source Data File Format**
	☐ *Airborne Laser*	☐ *Ground LiDAR DTM*	☐ *ASPRS .las/.laz (version ___)*
	☐ *Stereo Imagery*	☐ *DTM extracted by SGM*	☐ *Other: ___________________*
	☐ *Airborne Radar*	☐ *Derived using InSAR*	
	☐ *Space-Borne Radar*	☐ *Other: _______________*	

	Parameter	**Value**
Reference System	*Horizontal Datum:*	
	Projection System:	
	Vertical Datum:	
	Geoid Model:	

Notes:	

Appendix C: Accuracy Reporting

Table 6 and Table 7 shall be used by the data supplier to report the horizontal and vertical accuracies of the source data as well as the vertical accuracy of the DEMs delivered (modified from [1]).

Equations used to calculate the values in the reports:

Residual Errors

$$\Delta = \frac{\sum(N_i - N_i')}{n}$$

where:

N_i is the ith measured coordinate being evaluated, in the specified direction

N_i' is the corresponding check point ith coordinate for the points being evaluated, in the specified direction

i is an integer ranging from 1 to n and

n the number of control points

Mean Error

$$\bar{\Delta} = \frac{\sum \Delta_i}{n}$$

where:

Δ_i is the ith residual error in the specified direction

i is an integer ranging from 1 to n and

n the number of control points

Standard Deviation

$$\sigma = \sqrt{\frac{\sum(\Delta_{i-}\bar{\Delta})^2}{(n-1)}}$$

where:

Δ_i is the i^{th} residual error in the specified direction

$\bar{\Delta}$ is the mean error is the specified direction

i is an integer ranging from 1 to n and

n the number of control points

Root-Mean-Square Error

$$RMSE_N = \sqrt{\sum \frac{\left(N_i - N_i'\right)^2}{n}}$$ (1dRMSE, at 68% probability)

where:

N_i is the i^{th} measured coordinate being evaluated, in the specified direction

N_i' is the corresponding check point ith coordinate for the points being evaluated, in the specified direction

i is an integer ranging from 1 to n and

n the number of control points

Radial Horizontal Accuracy

$$RMSE_r = \sqrt{(RMSE_x^2 + RMSE_y^2)} \quad \text{(1d RMSEr, at 63\% probability)}$$

where:

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

$RMSE_y$ is the RMSE in the y direction

Non-vegetated Vertical Accuracy

$$NVA = RMSE_z \ x \ 1.96$$ (at 95% Confidence Level)

Vegetated Vertical Accuracy

$$VVA = RMSE_z \ x \ 3.00$$ (at 95th Percentile)

Table 6. Accuracy Report for Source Data

Point ID	**Measured Values (metres)**			**Survey Check Point Values (metres)**			**Residuals (errors) (metres)**		
	Easting (x)	**Northing (y)**	**Elevation (z)**	**Easting (x)**	**Northing (y)**	**Elevation (z)**	**Δx Easting**	**Δy Northing**	**Δz Elevation**
GCP1									
GCP2									
GCP3									
GCP4									
GCP5									
GCP6									
GCP7									
GCP8									
GCP9									
GCP10									
GCP11									
GCP12									
GCP13									
GCP14									
GCP15									
GCP16									
GCP17									
GCP18									
GCP19									
GCP20									
Number of check points									
Mean Error									
Standard Deviation									
Root-Mean-Square Error RMSE, 1dRMSE at 68% Confidence Level									
Radial Horizontal Accuracy RMSE$_r$, 1dRMSE$_r$ at 63% Confidence Level									
Horizontal Accuracy (ACCr) at 95% Confidence Level									
Non-vegetated Vertical Accuracy (NVA) at 95% Confidence Level									
Vegetated Vertical Accuracy (VVA) at 95th Percentile									

Table 7. Accuracy Report for DEM Products

Point ID	**Measured Values**	**Survey Check Point Values**			**Residuals (errors) (metres)**
	Elevation (z)	**Easting (x)**	**Northing (y)**	**Elevation (z)**	**Δz Elevation**
VP1					
VP2					
VP3					
VP4					
VP5					
VP6					
VP7					
VP8					
VP9					
VP10					
VP11					
VP12					
VP13					
VP14					
VP15					
VP16					
VP17					
VP18					
VP19					
VP20					
Number of Checkpoints					
Mean Error					
Standard Deviation					
Root-Mean-Square Error RMSE, 1dRMSE at 68% Confidence Level					
Non-vegetated Vertical Accuracy (NVA) at 95% Confidence Level					
Vegetated Vertical Accuracy (VVA) at 95th Percentile					

Appendix D: Example GeoTIFF Header

```
Size is 7665, 5155
Coordinate System is:
COMPOUNDCRS["NAD83(CSRS) / UTM zone 10N + CGVD2013 height",
    PROJCRS["NAD83(CSRS) / UTM zone 10N",
        BASEGEOGCRS["NAD83(CSRS)",
            DATUM["NAD83 Canadian Spatial Reference System",
                ELLIPSOID["GRS 1980",6378137,298.257222101,
                    LENGTHUNIT["metre",1]]],
            PRIMEM["Greenwich",0,
                ANGLEUNIT["degree",0.0174532925199433]],
            ID["EPSG",4617]],
        CONVERSION["UTM zone 10N",
            METHOD["Transverse Mercator",
                ID["EPSG",9807]],
            PARAMETER["Latitude of natural origin",0,
                ANGLEUNIT["degree",0.0174532925199433],
                ID["EPSG",8801]],
            PARAMETER["Longitude of natural origin",-123,
                ANGLEUNIT["degree",0.0174532925199433],
                ID["EPSG",8802]],
            PARAMETER["Scale factor at natural origin",0.9996,
                SCALEUNIT["unity",1],
                ID["EPSG",8805]],
            PARAMETER["False easting",500000,
                LENGTHUNIT["metre",1],
                ID["EPSG",8806]],
            PARAMETER["False northing",0,
                LENGTHUNIT["metre",1],
                ID["EPSG",8807]]],
        CS[Cartesian,2],
            AXIS["easting",east,
                ORDER[1],
                LENGTHUNIT["metre",1]],
            AXIS["northing",north,
                ORDER[2],
                LENGTHUNIT["metre",1]],
        ID["EPSG",3157]],
    VERTCRS["CGVD2013(CGG2013) height",
        VDATUM["Canadian Geodetic Vertical Datum of 2013 (CGG2013)"],
        CS[vertical,1],
```

```
            AXIS["gravity-related height",up,
                LENGTHUNIT["metre",1]],
        ID["EPSG",6647]]]
Data axis to CRS axis mapping: 1,2,3
Origin = (403676.000000000000000,5372746.000000000000000)
Pixel Size = (1.000000000000000,-1.000000000000000)
Metadata:
  AREA_OR_POINT=Area
Image Structure Metadata:
  COMPRESSION=LZW
  INTERLEAVE=BAND
Corner Coordinates:
Upper Left  (  403676.000, 5372746.000) (124d18'14.25"W, 48d30' 1.60"N)
Lower Left  (  403676.000, 5367591.000) (124d18' 9.98"W, 48d27'14.69"N)
Upper Right (  411341.000, 5372746.000) (124d12' 0.79"W, 48d30' 5.66"N)
Lower Right (  411341.000, 5367591.000) (124d11'56.86"W, 48d27'18.74"N)
Center      (  407508.500, 5370168.500) (124d15' 5.47"W, 48d28'40.22"N)
Band 1 Block=512x512 Type=Float32, ColorInterp=Gray
  Min=-4.435 Max=198.198
  Minimum=-4.435, Maximum=198.198, Mean=75.781, StdDev=49.401
  NoData Value=-32767
  Unit Type: metre
  Metadata:
    STATISTICS_MAXIMUM=198.19790649414
    STATISTICS_MEAN=75.781298053698
    STATISTICS_MINIMUM=-4.4346828460693
    STATISTICS_STDDEV=49.401037112729
```

List of Acronyms

1dRMS	One dimensional root-mean-square error
2dRMS	Two distance root-mean-square error
AGL	Aircraft altitude above ground level at nadir position
ASPRS	American Society for Photogrammetry and Remote Sensing
AT	Aerial Triangulation
BCGS	BC Geographic Series
DEM	Digital Elevation Model
DSM	Digital Surface Model
DTM	Digital Terrain Model
FGDC	Federal Geographic Data Committee
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSD	Ground Sample Distance
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
InSAR	Interferometric Synthetic Aperture Radar
LiDAR	Light Detection and Ranging
LZW	Lempel-Ziv-Welch lossless compression algorithm
NPD	Nominal Point Density
NPS	Nominal Point Spacing
NRGB	Normalized RGB
NSSDA	National Standards for Spatial Data Accuracy
NVA	Non-vegetated Vertical Accuracy
QL	Quality Level
RAD	Radians
$RMSE_r$	Horizontal Root-Mean-Square Error (radial)
$RMSE_x$	Horizontal (x) Root-Mean-Square Error
$RMSE_y$	Horizontal (y) Root-Mean-Square Error
$RMSE_z$	Vertical (z) Root-Mean-Square Error
SAR	Synthetic Aperture Radar
SGM	Semi-Global Matching
TIN	Triangular Irregular Networks
UAV	Unmanned Aerial Vehicle
VVA	Vegetated Vertical Accuracy
XML	Extensible Markup Language

Glossary of Terms

Source: modified from Heidemann [12] and ISO/TC 211 [15]

Absolute accuracy - 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 - The closeness of an estimated value (measured or computed) to a standard or accepted (true) value of a particular quantity. Related to the source data and DEM products quality.

- **Absolute accuracy** - 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.
- **Horizontal accuracy** - Positional accuracy of a dataset with respect to a horizontal datum. According to the National Standards for Spatial Data Accuracy (NSSDA), the radial horizontal accuracy (ACCr) is the radius of a circle of uncertainty, such that the true or theoretical location of the point falls within that circle 95% of the time.
- **Measurement accuracy** - Closeness of agreement between a test result or measurement result and the true value.
- **Positional accuracy** - The accuracy of the position of features, including horizontal and vertical positions, with respect to horizontal and vertical datums.

Active sensor - Sensor that generates the energy that it uses to perform the sensing.

Aerial triangulation (AT) - Process of developing a network of horizontal and or vertical positions from a group of known positions using direct or indirect measurements from aerial photographs and mathematical computations.

Altitude – The aircraft altitude above ground level (AGL) at nadir position. In this context, altitude is a height measured with respect to the underlying ground surface.

Artifacts – Buildings, towers, telephone poles or other elevated features that should be removed when depicting a DEM of the bare-earth terrain. Artifacts are not just limited to real features that need to be removed. They also include unintentional by-products of the production process, such as stripes in manually profiled DEMs.

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

Beam divergence - The beam divergence of an electromagnetic beam (for example, the laser used in LiDAR) is an angular measure of the increase in beam diameter or radius with distance from the optical aperture or antenna aperture from which the electromagnetic beam emerges.

Bias – A systematic error inherent in measurements due to some deficiency in the measurement process or subsequent processing.

Blunder – A mistake resulting from inattention, carelessness, or negligence.

Breaklines – Linear features that describe a change in the smoothness or continuity of the surface.

Calibration - Process of quantitatively defining a system's responses to known, controlled signal inputs.

Classification (of LiDAR) - The classification of LiDAR point clouds 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 built-up 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% confidence level means that 95% 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.

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

Coordinates – A pair or triplet of numbers that define a point in 2D or 3D space, respectively. Traditionally, a vertical coordinate would be defined as a 3D coordinate, that is, a x/y coordinate with an associated z-value.

Correction - Compensation for an estimated/measured systematic effect.

Data product - Dataset or dataset series that conforms to a data product specification.

Data product specification - Detailed description of a dataset or dataset series together with additional information that will enable it to be created, supplied to and used by another party.

Dataset - Identifiable collection of data.

Datum - A set of reference points on the Earth’s surface from 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 are used for describing a point on the Earth's surface, in latitude and longitude or another coordinate system. Vertical datums are used to measure elevations or depths.

Delaunay triangulation - Network of triangles such that the circle passing through the vertices of any triangle does not contain, in its interior, the vertex of any other triangle.

Digital Elevation Model (DEM) – Digital representation of continuous elevation values over a topographic functional surface by a regular or irregular array of z-values. DEM normally implies x, y coordinates and z-values of the bare-earth terrain, void of vegetation and built-up features.

Digital Elevation Model (DEM) resolution – The smallest distance between two discrete points that can be explicitly represented in a gridded elevation model. It is important to note that features of a size equal to, or even greater than the resolution, may not be detected or explicitly represented in a gridded model. For gridded elevation data the horizontal resolution may be referenced as the point spacing, cell size, grid spacing or the ground sample distance.

Digital Surface Model (DSM) – Similar to DTM, except that they 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, forest management, air safety, 3D modeling and simulation.

Digital Terrain Model (DTM) - Computer representation of terrain stored in a digital data file as a set of discrete points with 3D coordinates, Easting (x), Northing (y) and elevation (z).

Easting - Distance in a coordinate system, eastwards (positive) or westwards (negative) from a north-south reference line.

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

Error - Measured quantity value minus a reference quantity value.

First return - First reflected signal that is detected by a 3D imaging system, for a given sampling position and a given emitted pulse.

Focal length - The focal length of an optical system is a measure of how strongly the system converges or diverges light or the distance between the perspective center and the image plane that is the result of balancing positive and negative radial lens distortions during sensor calibration.

Format - Language construct that specifies the representation, in character form, of data objects in a record, file, message, storage device, or transmission channel.

Geographic Coordinate System (GCS) - A 2D coordinate system defined by latitude and longitude, based on a reference ellipsoid approximation of the earth. Latitude and longitude are based on the angle from the equator and prime meridian respectively.

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

Geoid - The equipotential surface that coincides with the mean ocean surface of the earth. A smooth but highly irregular surface, known by gravitational measurements, to which the force of gravity is everywhere perpendicular.

Georeferencing – Positioning the reference frame of a spatial dataset in real world coordinates.

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 remote sensing, mapping, and surveying technologies. Geospatial data generally are synonymous with spatial data; however, geospatial data always are associated with geographic or Cartesian coordinates linked to a horizontal or vertical datum, whereas spatial data may exist in an arbitrary coordinate system.

Global Navigation Satellite System (GNSS) - A constellation of radio-emitting satellites used to determine positions of receivers. The satellites transmit signals that allow a receiver to calculate its location through trilateration.

Global Positioning System (GPS) - A system of radio-emitting and -receiving satellites used to determine positions on the earth. Orbiting satellites transmit signals that allow a GPS receiver to calculate its own location through trilateration (determining position with respect to two other points by measuring the distance between all three points).

Ground Sample Distance (GSD) – The linear dimension of a sample pixel's footprint on the ground. Value computed using the calibrated camera focal length and average camera height above horizontal terrain.

Horizontal accuracy (*see Radial Accuracy)* - Positional accuracy of a dataset with respect to a horizontal datum. According to the NSSDA, the radial horizontal accuracy (ACCr) is the radius of a circle of uncertainty, such that the true or theoretical location of the point falls within that circle 95% of the time.

Hydrological flattening (hydro-flattened) - Processing of a DEM so that mapped water bodies, 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, consistent with their natural behavior and the surrounding topography. The process of hydro-flattening typically involves the addition of breaklines along the banks of specified water bodies, 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 or hydraulic modeling requirements but solely by cartographic mapping needs [13].

Inertial Measurement Unit (IMU) - The combination of a 3-axis accelerometer combined with a 3-axis gyroscope. An onboard processor, memory, and temperature sensor may be included to provide a digital interface, unit conversion and to apply a sensor calibration model. The IMU by itself does not provide any kind of navigation solution (position, velocity, attitude). It only actuates as a sensor, as part of the INS (Inertial Navigation System), which integrate the measurements of its internal IMU to provide a navigation solution.

Inertial Navigation System (INS) – A self-contained navigation system, comprised of several subsystems: IMU, navigation computer, power supply, interface, etc. Uses measured accelerations and rotations to estimate velocity, position, and orientation. An unaided INS loses accuracy over time, due to gyroscopic drift.

Intensity (LiDAR) - For discrete-return LiDAR instruments, intensity is the recorded amplitude of the reflected LiDAR pulse at the time 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 cannot be equated to a true measure of energy. LiDAR intensity data make it possible to map variable textures in the form of a gray-scale image. Intensity return data enable automatic identification and extraction of objects such as buildings and impervious surfaces and can aid in LiDAR point classification.

Interferometric Synthetic Aperture Radar (InSAR) - A dual-antenna radar sensor mounted on an airborne or space-borne platform that collects a remotely sensed radar image, called an interferogram. There is a measured energy shift between the signals received by each antenna, and this interference can be colourized to measure elevation or changes in the topography on the earth's surface.

Interpolation – Procedure used to estimate the elevation at a location lacking measurement data, where there are measurements surrounding that location. Interpolation is based on the principle of spatial autocorrelation, which assumes that closer points are more similar in elevation than farther points.

Last return - Last reflected signal that is detected by a 3D imaging system, for a given sampling position and a given emitted pulse.

Lattice – A 3D surface 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 mesh points of the lattice, rather than the value of the cell area surrounding each mesh point.

Light Detection and Ranging (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. This distance conversion, combined with position and attitude information from GPS, INS, and the instrument itself, allows the derivation of the 3D coordinates of the reflecting target's point location.

Low Confidence Areas - Areas where the vertical data may not meet the data accuracy requirements due to heavy vegetation even though the specified nominal pulse spacing was met or exceeded.

Mass points – Irregularly spaced points, each with an x/y location and a z-value, used to form a DTM. When generated manually, mass points are ideally chosen to depict the most significant variations in the slope or aspect of the terrain. However, when generated by automated methods, for example, by LiDAR or InSAR scanners, mass point spacing, and pattern depend on characteristics of the technologies used to acquire the data. Mass points are most often used to make a TIN or derive a gridded DEM by interpolation.

Measurement accuracy - Closeness of agreement between a test result or measurement result and the true value.

Measurement error - Measured quantity value minus a reference quantity value.

Measurement precision - Closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions.

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 [11] metadata), reports (collection, processing, Quality Assurance/Quality Control (QA/QC)), and other supporting data (for example, survey points, shapefiles).

Model – Abstract representations of some aspects of reality.

NoData (null value) - In raster data, the absence of a recorded value. NoData does not equate to a zero value. While the measure of a particular attribute in a cell may be zero, a NoData value indicates that no measurements have been taken for that cell at all.

Nominal Pulse Density (NPD) - A common measure of the density of a LiDAR dataset; NPD is the typical or average number of pulses occurring in a specified areal unit. The NPD is typically expressed as pulses per square meter (pls/m^2). 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. NPD can be calculated from NPS using the formula:

$$NPD = 1/NPS^2$$

Nominal Pulse Spacing (NPS) - As a common measure of the density of a LiDAR dataset, NPS is the typical or average lateral distance between pulses, typically expressed in metres and most simply calculated as the square root of the average area per first return points. 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. NPS can be calculated from Nominal Point Density (NPD) using the formula:

$$NPS = 1/\sqrt{NPD}$$

Non-vegetated Vertical Accuracy (NVA) - The vertical accuracy at the 95% confidence level in non-vegetated open terrain.

Noise - Unwanted signal which can corrupt the measurement of features. Noise may arise due to poor scanner calibration or environmental factors.

Northing - Distance in a coordinate system, northwards (positive) or southwards (negative) from an east-west reference line.

Passive sensor - Sensor that detects and collects energy from an independent source.

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 VVA. Note that percentile calculations are based on the absolute values of the errors, as it is the magnitude of the errors, not the sign that is of concern.

The percentile rank (*n*) is first calculated for the desired percentile using the following equation:

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

where:

n is the rank of the observation that contains the P^{th} percentile,

P is the proportion (of 100) at which the percentile is desired (for example, 95 for 95^{th} percentile),

N is the number of observations in the sample data set.

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:

$$Q_p = \left(A[n_w] + \left(n_d(A[n_w + 1] - A[n_w\}))\right)\right)$$

where:

Qp is the P^{th} percentile; the value at rank n,

A is an array of the absolute values of the samples, indexed in ascending order from 1 to N,

A(i) is the sample value of array A at index i (for example, n_w or n_d). i must be an integer between 1 and N,

n is the rank of the observation that contains the P^{th} percentile,

n_w is the whole number component of n (for example, 3 of 3.14),

n_d is the decimal component of n (for example, 0.14 of 3.14).

Pitch - Objects that are free to operate in three dimensions, such as aircraft, can change their attitude by rotating about the three orthogonal axes centered on the vehicle's center of gravity — the longitudinal, vertical, and lateral axes. Motion about the lateral axis is called pitch and it is a measure of how far an airplane's nose is tilted up or down.

Plumb Line - A line that corresponds to the direction of gravity at a point on the earth's surface; the line along which an object will fall when dropped.

Positional accuracy - The accuracy of the position of features, including horizontal and vertical positions, with respect to horizontal and vertical datums.

Positioning system - System of instrumental and computational components for determining position.

Platform - Structure which supports a sensor, or sensors.

Precision - Measure of the repeatability of a set of measurements. The closeness with which measurements agree with each other, even though they may all contain a systematic bias.

Projected coordinate reference system - A method used to represent the curved, 3D surfaces of the earth on a 2D plane. Essentially, the conversion of location data from a sphere approximation to a planar surface (e.g., UTM).

Quality - Degree to which a set of inherent characteristics fulfils requirements. Accuracy (exactitude) and precision (repeatability) are the means used to evaluate the quality of the source data and DEM products.

Quality Assurance (QA) - Set of activities for ensuring quality in the processes by which products are developed. In particular, the measures taken to ensure the quality of the source data, before and during acquisition of the data.

Quality Control (QC) - Set of activities for ensuring quality in products. The activities focus on identifying defects in the actual products produced. The verification of the quality of the deliverables is part of the QC.

Radial Accuracy (ACCr) *(see Horizontal Accuracy)* - The National Standards for Spatial Data Accuracy (NSSDA) [16] 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. ACCr = 1.7308 x $RMSE_r$

Radian (rad) - The radian is the standard unit of angular measure, used in many areas of mathematics. An angle's measurement in radians is numerically equal to the length of a corresponding arc of a unit circle; one radian is just under 57.3 degrees (when the arc length is equal to the radius).

Raster - Array of regularly sized, continuous cells with single values associated with each cell. In the case here, bare-earth elevation values at the centre of each cell are assigned to the whole cell area.

Remote sensing - Collection and interpretation of information about an object without being in physical contact with the object.

Roll - Objects that are free to move in three dimensions, such as an aircraft, can change their attitude by rotating about the three orthogonal axes centered on the vehicle’s center of gravity — the longitudinal, vertical, and lateral axes. Motion about the longitudinal axis is called roll and it determines how much the wings of the aircraft are banked.

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 (RMSE_x and RMSE_y) and vertical (RMSE_z) coordinates where standard or accepted values are known, as with GPS-surveyed control points of higher accuracy than the data being tested.

The standard equations for calculating horizontal and vertical RMSE are provided here:

RMSE_x The horizontal root-mean-square error in the x direction (Easting):

$$\sqrt{\sum \frac{(X_i - X_i')^2}{n}}$$

where:

X_i is the set of n x coordinates being evaluated,

X_i' is the corresponding set of check point x coordinates for the points being evaluated,

n is the number of x coordinate check points, and

i is the identification number of each check point from 1 through n.

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

$$\sqrt{\sum\frac{(Y_i - Y_i')^2}{n}}$$

where:

Y_i is the set of n y coordinates being evaluated,

Y_i' is the corresponding set of check point y coordinates for the points being evaluated,

n is the number of y coordinate check points, and

i is the identification number of each check point from 1 through n.

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

$$\sqrt{\sum\frac{(Z_i - Z_i')^2}{n}}$$

where:

Z_i is the set of n z values (elevations) being evaluated,

Z_i' is the corresponding set of check point elevations for the points being evaluated, *n* is the number of z check points, and

i is the identification number of each check point from 1 through n.

Semi-Global Matching (SGM) – Method of finding correspondences for every pixel, supported by a global cost function, which is optimized in 8 path directions across the image. The method has a regular algorithmic structure, uses simple operations, and offers a good mixture of speed, quality and robustness. On the other hand, this technique does not support proper georeferencing like LiDAR and is prone to generate larger outliers when extracting points for ambiguous features. SGM results in DSMs instead of DTMs because such correlation generates elevations of rooftops, treetops and other surface features as imaged on the stereo photographs.

Stereo photogrammetry – Involves estimating the x, y and z coordinates of points employing measurements made from two or more aerial photographic images taken from different positions, using stereo matching methods.

Sensor – Element of a measuring system that is directly affected by a phenomenon, body, or substance carrying a quantity to be measured.

Supplier - Organization or person that provides a product.

Synthetic Aperture Radar (SAR) - Imaging radar system that simulates the use of a long physical antenna by collecting multiple returns from each target as the actual antenna moves along the track.

Tessellation - The division of a two-dimensional area into polygonal tiles, or a three-dimensional area into polyhedral blocks, in such a way that no figures overlap and there are no gaps.

Vegetated vertical accuracy (VVA) - An estimate of the vertical accuracy, based on the 95th percentile, in vegetated terrain.

Vertical accuracy - The measure of the positional accuracy of a dataset with respect to a specified vertical datum, at a specified confidence level or percentile. Indicator of quality for DEM products.

Triangulated Irregular Network (TIN) – A set of adjacent, nonoverlapping triangles computed from irregularly spaced points with x/y coordinates and z-values. The TIN model stores the topological relationship between triangles and their adjacent neighbors. The TIN data structure allows for the efficient generation of surface models for the analysis and display of terrain and other types of surfaces. TINs can capture critical points that define terrain discontinuities and are topologically encoded so that adjacency and proximity analyses can be performed. TINs have several advantages over gridded DEMs, including better surface modeling.

Yaw - Objects that are free to move in three dimensions, such as an aircraft, can change their attitude by rotating about the three orthogonal axes centered on the vehicle's center of gravity — the longitudinal, vertical, and lateral axes. Motion about the vertical axis is called yaw and it determines which way the nose of the aircraft is pointed. (Note: Aircraft do not necessarily fly in the same direction as the nose is pointed if there are significant winds).

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