Specifications for the Production of Digital Elevation Models for the Province of British Columbia

GeoBC
Ministry of Forest, Lands and Natural Resources Operations GeoBC

Version 2.2, May 2017
Victoria (BC), Canada
Table of Contents

1.0 RECORD OF AMENDMENTS ......................................................................................... 4
2.0 INTRODUCTION ............................................................................................................ 5
3.0 PURPOSE AND SCOPE ................................................................................................. 5
4.0 DIGITAL DATA MODEL DESCRIPTION ....................................................................... 5
  4.1 Digital Terrain Model (DTM) ....................................................................................... 5
  4.2 Digital Elevation Model (DEM) .................................................................................. 8
  4.2.1 Gridded DEM ......................................................................................................... 8
  4.2.2 TIN DEM ............................................................................................................... 9
  4.2.3 Interpolation methods ........................................................................................... 10
  4.2.4 Comparison of DEM types .................................................................................... 12
5.0 SOURCE DATA REQUIREMENTS ................................................................................. 13
  5.1 Stereo Matching ....................................................................................................... 15
  5.2 LiDAR ......................................................................................................................... 16
  5.3 SGM versus LiDAR for DSMs generation ................................................................. 16
  5.4 Other data sources ................................................................................................... 17
6.0 ACCURACY REQUIREMENTS ....................................................................................... 18
  6.1 Vertical Accuracy ...................................................................................................... 18
    6.1.1 Non-vegetated Vertical Accuracy (NVA) ............................................................ 18
    6.1.2 Vegetated Vertical Accuracy (VVA) .................................................................... 18
  6.2 Horizontal Accuracy ................................................................................................. 19
    6.2.1 Estimation of Horizontal Accuracy (RMSEh) based on LiDAR ......................... 19
    6.2.2 Estimation of Horizontal Accuracy (RMSEh) based on Photogrammetry ......... 20
    6.2.2.1 Indirect georeferencing (aerial triangulation) ............................................. 20
    6.2.2.2 Direct georeferencing (GPS/INS) .............................................................. 20
  7.0 QUALITY LEVELS ..................................................................................................... 21
8.0 REQUIREMENTS FOR DELIVERABLES ................................................................... 21
9.0 REFERENCES ............................................................................................................... 27
APPENDIX A HYDROLOGIC TREATMENTS .................................................................... 29
APPENDIX B ASPRS (2014) REFERENCES TABLES ......................................................... 33
APPENDIX C REQUIREMENTS CHECKLIST .................................................................... 35
APPENDIX D ACCURACY REPORTING ......................................................................... 36
APPENDIX E FILES NAMING CONVENTIONS .............................................................. 39

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### 1.0 RECORD OF AMENDMENTS

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<td>Isabelle Paquin</td>
<td>1-48</td>
<td></td>
<td>Harald Steiner, P. Eng.</td>
<td><a href="mailto:Harald.Steiner@gov.bc.ca">Harald.Steiner@gov.bc.ca</a></td>
<td>21-Apr-2016</td>
</tr>
<tr>
<td></td>
<td>Brett Edwards</td>
<td></td>
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<td>Robert Prins</td>
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Owner: GeoBC
Title: Specifications for the Production of Digital Elevation Models for the Province of British Columbia
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2.0 INTRODUCTION

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

For the purpose of 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 (GEOBC) of the Ministry of Forest Land and Natural Resources Operations in the Province of British Columbia. The Branch shall be the final authority on acceptance or rejection of submitted Digital Elevation Model results, products and materials.

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

3.0 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” (edition 1, version 1.0 – November 2014) 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 Digital Elevation Models, including the final resolution and accuracy of the models, the descriptive metadata, spatial reference system information and relevant reports to be delivered (see Section 8.0).

4.0 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.

4.1 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 3-dimensional coordinates; easting (x), northing (y) and elevation (z).
It is often a derived product of a Digital Surface Model (DSM) which include all the features of the surface (Figure 2 and Figure 3) while the DTM represents the bare ground surface of the terrain, excluding vegetation and manmade features.

Note on Elevation Types

Two main elevation types or "heights" are explained below. Unless specified to the contrary in the project requirements, the elevation of any point shall be its orthometric height by default.

Orthometric Height: The 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.

Ellipsoidal Height: The 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. (NDEP, 2004)

Figure 1 illustrate the differences between the height types, where:

N = geoid separation (deviation between the Geoid and a reference ellipsoid)
H = Orthometric Height
h = Ellipsoidal Height
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) in the derived elevation model, as needed.
4.2 Digital Elevation Model (DEM)

A DEM is a digital representation of continuous elevation values over a topographic functional surface by a regular or irregular array of z-values. Even though there are other means of representing a digital surface from DTM points, the specifications in this document are applicable mainly to two widely used types of DEMs; gridded DEMs and vector-based Triangular 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 4). Those products derived from DEMs are not covered by these requirements.

The term DEM, when used alone from this point forward in these specifications, shall be applicable to both gridded DEM and vector-based TIN.

4.2.1 Gridded DEM

Tessellation is the complete and continuous partitioning of a surface into mutually exclusive spatial units where each cell has a value that characterizes that portion of space. Tessellation may be of either regular or irregular shape. Several types of regular tessellations, i.e. where the cells are the same shape and size, can be used, for example squares, hexagons or equilateral triangles. Squares are the simplest (and most commonly used) regular tessellation to derive DEMs, mainly because georeferencing a square cell is so straightforward.

Figure 4. Typical Data Flow from DSM to derived products
Two types of regular tessellations using squares to store the elevation data are often confused, some sources will refer to Grid and Lattice but others will talk about Raster and Grid, with different definitions for each. For the sake of clarity, the Branch shall make the following distinction between a raster and a lattice, as applicable to these requirements used for the production of DEMs.

A raster shall be defined as a set of regularly spaced, continuous cells with, in the case here, bare-earth elevation values attached to the center of each cell and the value for a cell is assumed to be valid for the whole cell area. Raster centroids coordinates are contained in the arrangement of the matrix. See Figure 5A for an illustration of the “step effect” caused by raster cells (height fields).

As for the lattice, it 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 5B 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. As they are derived from DTM, bare-earth gridded DEMs are free from vegetation, buildings, bridges and other man-made structures. Unless specified otherwise in the project requirements, the roads at ground level shall be kept by default, classified as ground. In regard to these specifications, the term gridded DEM is used instead of raster DEM.

![Figure 5. Differences between a Raster and a Lattice](image)

4.2.2 TIN DEM

For irregular tessellations, the surface is also partitioned into mutually disjoint cells but those cells vary in size and shape, so they can adapt to the surface they represent.
The Triangular Irregular Networks (TIN) is one of the most frequently used vector-based representations for the storage of surface models information, although it can be considered a hybrid between tessellations and vector representations. 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, from the mass points of the source dataset, an irregular tessellation can be made out of triangles to create planes representing the surface, so it can be considered another form of DEM than the gridded model (Figure 6). The most common triangulation is the Delaunay, 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 as close as possible to a node while reducing the problems created by “skinny” triangles.

![Sampling points/lines](Image)

(a) Grid Points
(b) Random Points

Figure 6. Gridded DEM and TIN

4.2.3 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 closer points are more similar 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 shall be used by default, unless otherwise specified in the project requirements by the Branch. The interpolation from contour lines shall not be used to derive DEMs.

Bicubic interpolation maintains the continuity of the function and is often chosen over bilinear interpolation or nearest neighbour, when processing time is not an issue. In contrast to bilinear interpolation, which only takes 4 pixels (2×2) into account, bicubic interpolation considers 16 pixels (4×4). DEMs derived from DTMs using bicubic interpolation are smoother and have fewer interpolation artifacts.

As an example, Figure 7 shows a bicubic interpolation done on a square consisting of 9 unit squares patched together. Color indicates function value and the black dots are the locations of the prescribed data being interpolated. Note how the color samples are not radially symmetric. Figure 8 shows bilinear interpolation done on the same dataset. Derivatives of the surface are not continuous over the square boundaries. The result of the nearest-neighbour interpolation, also done on the same dataset, is shown in Figure 9. Note that the information content in all these three examples is equivalent.

![Figure 7. Example of the result of bicubic interpolation](image-url)

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4.2.4 Comparison of DEM types

Depending on the project specific requirements, the supplier shall provide either gridded DEMs or vector-based TINs, or both. But the user/project manager must decide which type of DEM is the best choice. There are no clear-cut recommendations for that choice since this decision will be based on several criteria, which may be differ between projects. For example, the intended use of the model, the final resolution needed, the financial and storage constraints on the user side, the software available for viewing and editing the models need to be known and taken into consideration before making the decision on which model to use. Table 1 list some examples of advantages and disadvantages for each model.
Table 1. Comparison of model types

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

5.0 SOURCE DATA REQUIREMENTS

In this section, a brief description of the most common source data that can be used for DEM production is provided. When delivering DEMs the data suppliers shall provide reports indicating that the absolute accuracy and precision of the source data meet or exceed the requirements for the derived DEM since interpolation and/or smoothing will, amongst other factors, affect negatively the level of 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:

1) Ground survey techniques: notably the accurate surveying of ground-based point locations. This technique is mostly used for ground control points collection of source data and not for the DEM derivation itself.

2) Existing topographic maps: the derivation of contours, streams, lakes, and elevation points from hardcopy topographic maps. This involves the digitizing and semi-automatic scanning of raster images of topographic maps to convert them into vectors. Those techniques shall not be considered a source of derived DEM in this document.

3) Remote sensing: The acquisition of information about an object without making physical contact with the object, either with passive or active sensors. Here, the processing and interpretation of images and data
acquired from airborne (or satellite platforms in certain cases) sensors shall be considered the main source of elevation data used to derive DEMs.
Parallel to the evolution of laser and radar based elevation data, software advancements and the rapid development of low-cost and effective Unmanned Aerial Vehicles (UAVs) as well as cameras capable of obtaining high quality aerial photographs and video has open even more interesting options in the near future. The main advantages of these platforms are their relative low cost, less dependence on contractor schedules, direct georeferencing, quick turn-around for geospatial products and the flexibility to select the conditions and fly as frequently as necessary to achieve a desired result. On the other hand, for projects covering large and remote or inaccessible areas it may be more profitable in terms of time and money to use conventional platforms. New data acquisition technologies currently being developed and perfected may become important sources of elevation data in the future but any deviation from the requirements must be approved by the Branch prior to being used by the suppliers.

5.1 Stereo Matching

Aerial photography is a passive remote sensing technique which measure 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 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 processes of recording, measuring and interpreting photographic images.

Stereo photogrammetry is the 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 of the cameras. 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 that offers a good tradeoff between accuracy and runtime and is well suited for accurate 3D reconstruction from images from stereo images. It is the method that shall be used by default for generating 3D point clouds from 2D stereo imagery.

SGM tries to find 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 is prone to generate larger outliers when extracting points for ambiguous features. See Section 5.3 for a general comparison between mass point clouds generated by SGM and LiDAR. For more detailed information about SGM, consult the references list (Hirschmüller, 2008, 2010 and 2011).
When stereo photogrammetry is the source of the derived DEM, suppliers shall ensure that the horizontal accuracy and GSD of the images used as well as the points spacing/density of the final mass points DTM exceed the requirements for the derived DEM (see Sections 6 and 7). All systemic errors and bias shall be addressed and corrected before deriving DEMs. Furthermore, no points shall be added to the mass points using linear interpolation.

5.2 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 elevation. LiDAR systems are complex, multi-sensor systems consisting of at least three sensors, a laser range-finder, a Global Positioning System (GPS), 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 in order to achieve the required LiDAR points accuracy.

![Diagram of LiDAR production steps](image)

Figure 10. General production steps for LiDAR for DTM generation

The general production steps are shown in Figure 10. General production steps for LiDAR for DTM generation, each of which will affect the final accuracy of the derived products. Consult “GeoBC Specifications for LiDAR, v1.0 (2013)” for more information on the requirements applicable to LiDAR source data.

When LiDAR is the source of the derived DEM, suppliers shall ensure that the horizontal accuracy as well as the points spacing/density of the final mass points DTM exceed the requirements for the derived DEM (see Sections 6 and 7). All systemic 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.

5.3 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

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

5.4 Other data sources

Other active sensor systems similar to LiDAR make use of other parts of the electromagnetic spectrum and can be generate datasets 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 (aircrafts) platforms. The term RADAR was coined in 1940 by the United States Navy as an acronym for RAdio Detection And Ranging. The term radar has since entered English and other languages as a common noun, losing the capitalization.

SAR/InSAR

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 sensors 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, the image acquisition 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 prevented by cloud cover.

To create a SAR image, successive pulses of radio waves are transmitted to "illuminate" a target scene, and the echo of each pulse is received and recorded. The pulses are transmitted and the echoes received using a single beam-forming
antenna, with wavelengths of a metre down to several millimetres. As the SAR device on board the aircraft or spacecraft moves, the antenna location relative to the target changes with time. Signal processing of the successive recorded radar echoes allows the combining of the recordings from these multiple antenna positions and forms the synthetic antenna aperture.

Radargrammetry 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.

6.0 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 (2014). Also to align with the new 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).

6.1 Vertical Accuracy

6.1.1 Non-vegetated Vertical Accuracy (NVA)

Non-vegetated Vertical Accuracy relates to the measures done on the derived DEM compared to verification points. The orthometric height shall be used, i.e. 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 (Knippers, 2009).

NVA is an estimate of the derived DEM vertical accuracy at a 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 7.0).

Below are listed most of the non-vegetated cover types that may apply to a typical project but the Branch reserves the right to include or exclude specifics cover types in the project requirements.

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

By default, only the NVA shall be used for production and testing of the input mass data points, as well as for the verification done on the derived DEM, regardless of the cover type.

6.1.2 Vegetated Vertical Accuracy (VVA)

Authorization to use the VVA index in certain portion of the project area shall
be included in the project specific requirements only if it is allowed by the Branch. The 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. They shall get the project specific requirements amended before using the VVA for either the input data or the deliverables.

Vegetated Vertical Accuracy relates to the measures that shall be done on the derived DEM compared to verification points. The orthometric height shall be used; 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. 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 account for most of the errors due to noise and/or incorrect classification, it often entails the most time and efforts to correct.

Below are listed most of the vegetated cover types that may apply to a typical project but the Branch reserves the right to include or exclude specifics cover types in the project requirements.

- Vegetated land cover types includes, 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 has the responsibility to establish appropriate methodologies, applicable to the technologies used, to verify that vertical accuracies meet or exceed the stated project requirements. Reporting of the accuracy testing is described in Section 8.

### 6.2 Horizontal Accuracy

Horizontal errors are more difficult than vertical error to assess in the final DEMs. This is mainly because the bare-earth derived surface often lacks 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 in addition of the horizontal accuracy of the derived DEMs.

#### 6.2.1 Estimation of Horizontal Accuracy (RMSEh) based on LiDAR

\[
RMSE_h = \sqrt{\left(\theta_{laser} \times AGL\right)^2 + \left(\sigma_{GPS_{xy}}\right)^2 + \left(\sigma_{IMU_{pr}} \times AGL\right)^2}
\]

where:

- \(RMSE_h\) = Horizontal DEM accuracy over flat terrain (metres) at 63% probability
- \(\theta_{laser}\) = Laser beam divergence (rad)
6.2.2.2 Estimation of Horizontal Accuracy (RMSEr) based on Photogrammetry

6.2.2.1 Indirect georeferencing (aerial triangulation)

\[
\text{RMSEr} = \sigma_{XY_{AT}} = \sqrt{\left(\frac{\sigma_X \times AGL}{f}\right)^2 + \left(\frac{\sigma_Y \times AGL}{f}\right)^2}
\]

where:
- \(\text{RMSEr}\) = Horizontal DEM accuracy over flat terrain (metres) at 63% probability
- \(AGL\) = Aircraft altitude above ground level at Nadir position (metres)
- \(\sigma_X\) = Standard Deviation of the Image Measurement in the X axis, from the Bundle Block Adjustment (metres)
- \(\sigma_Y\) = Standard Deviation of the Image Measurement in the Y axis, from the Bundle Block Adjustment (metres)
- \(f\) = Focal Lenght (metres)

6.2.2.2 Direct georeferencing (GPS/INS)

\[
\text{RMSEr} = \sigma_{XY_{GPS/INS}} = \sqrt{\left(\frac{\sigma_{IMUr_p} \times AGL}{f}\right)^2 + \left(\frac{1}{3} GSD\right)^2}
\]

where:
- \(\text{RMSEr}\) = Horizontal DEM accuracy over flat terrain (metres) at 63% probability
- \(AGL\) = Aircraft altitude above ground level at Nadir position (metres)
- \(\sigma_{IMUr_p}\) = Average angular accuracy of the drift corrected IMU in roll and pitch orientation (rad)
- \(GSD\) = Ground Surface Distance (metres)
7.0 QUALITY LEVELS

In order to keep the quality of a DEM at the highest level, Digital Elevation Models 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, as long as the requirements of the designated Quality Level are met (see Table 3), can be used to generate the source data.

The values listed in Table 3 are defined as follow:

- **Quality Level (QL)** -> For every project, the Branch will 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 (RMSEₚ) 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 6.1.1).

- **VVA Required** -> Vegetated Vertical Accuracy relating to the measures done on the derived DEM vs verification points, at 95th Percentile (see Section 6.1.2).

- **DEM Grid Size** -> Maximum cell size, if the DEM is interpolated to a grid.

- **TIN Points Density** -> Minimum points density, if the DEM is a TIN.

Table 3. Requirements per Quality Level

<table>
<thead>
<tr>
<th>Quality Level</th>
<th>Accuracy Class</th>
<th>NVA required</th>
<th>VVA required</th>
<th>DEM Grid Size (m)</th>
<th>TIN Point Density (pts/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QL1</td>
<td>5.0 cm</td>
<td>± 9.80 cm</td>
<td>± 15 cm</td>
<td>≤ 0.50</td>
<td>&gt; 8</td>
</tr>
<tr>
<td>QL2</td>
<td>10 cm</td>
<td>± 19.6 cm</td>
<td>± 30 cm</td>
<td>1.0</td>
<td>&gt; 2</td>
</tr>
<tr>
<td>QL3</td>
<td>20 cm</td>
<td>± 39.2 cm</td>
<td>± 60 cm</td>
<td>2.0</td>
<td>&gt; 0.5</td>
</tr>
<tr>
<td>QL4</td>
<td>1.0 m</td>
<td>± 1.96 m</td>
<td>± 3 m</td>
<td>5.0</td>
<td>&gt; 0.05</td>
</tr>
<tr>
<td>QL5</td>
<td>3.0 m</td>
<td>± 6.53 m</td>
<td>± 10 m</td>
<td>≥ 10</td>
<td>&gt; 0.01</td>
</tr>
</tbody>
</table>

Appendix B shows the values taken from ASPRS (2014) that were used to establish the requirements values listed in Table 3.

8.0 REQUIREMENTS FOR DELIVERABLES

The “User Requirements Checklist” shall be completed by the Branch and list the
specific project requirements the suppliers shall follow. An example of the checklist showing some of the defaults requirements can be seen on the next page and the blank form can be found in Appendix C.
Table 4. Example of a User Requirement Checklist with defaults requirements

User Requirements Checklist for Project: ________________________________________________________________

<table>
<thead>
<tr>
<th>Quality Level</th>
<th>Model Type</th>
<th>Model Components</th>
<th>Supplemental Surface Treatments</th>
</tr>
</thead>
<tbody>
<tr>
<td>☐ QL1</td>
<td>Gridded DEM</td>
<td>☒ Bare-Earth</td>
<td>☐ Buildings Flattened</td>
</tr>
<tr>
<td>☐ QL2</td>
<td>TIN</td>
<td>☐ Hydro-Flattened</td>
<td>☒ DTM Points Thinned (factor:__)</td>
</tr>
<tr>
<td>☐ QL3</td>
<td>Source DTM</td>
<td>☒ Bridges Excluded</td>
<td>☐ Breaklines used for Model</td>
</tr>
<tr>
<td>☐ QL4</td>
<td>Other: _______</td>
<td>☒ Roads Class. as Ground</td>
<td>☐ Other: _____________________________</td>
</tr>
<tr>
<td>☐ QL5</td>
<td>Other: _______</td>
<td>☐ Other: _____________</td>
<td>☐ Other: _____________________________</td>
</tr>
</tbody>
</table>

Comments / User Waiver:

<table>
<thead>
<tr>
<th>Grid Cell Size (metres)</th>
<th>TIN Point Density (points/m²)</th>
<th>Source Data Technology</th>
<th>Source DTM Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>☐ ≤ 0.50</td>
<td>☐ &gt; 8</td>
<td>☐ Stereo Imagery</td>
<td>☒ DTM extracted by SGM</td>
</tr>
<tr>
<td>☐ 1.0</td>
<td>☐ &gt; 2</td>
<td>☐ Airborne Laser</td>
<td>☒ Ground LiDAR DTM</td>
</tr>
<tr>
<td>☐ 2.0</td>
<td>☐ &gt; 0.5</td>
<td>☐ Airborne Radar</td>
<td>☒ Derived using InSAR</td>
</tr>
<tr>
<td>☐ 5.0</td>
<td>☐ &gt; 0.05</td>
<td>☐ Space-borne Radar</td>
<td>☐ Other: _____________________________</td>
</tr>
<tr>
<td>☐ ≥ 10</td>
<td>☐ &gt; 0.01</td>
<td>☐ Other: ______________</td>
<td>☐ Other: _____________________________</td>
</tr>
<tr>
<td>☐ NA</td>
<td>☐ NA</td>
<td>☐ Other: _____________</td>
<td>☐ Other: _____________________________</td>
</tr>
</tbody>
</table>

Comments / User Waiver:

<table>
<thead>
<tr>
<th>Horizontal Datum</th>
<th>Coordinate System</th>
<th>Derived DEM File Format (extension)</th>
<th>Source Data File Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>☒ NAD 83</td>
<td>☒ UTM (Zone_______)</td>
<td>☐ ESRI TIN (.tin)</td>
<td>☐ Other: _____________________________</td>
</tr>
<tr>
<td>Vertical Datum</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>☐ bcalber</td>
<td></td>
<td>☐ ESRI GRID (.asc)</td>
<td>☐ Other: _____________________________</td>
</tr>
<tr>
<td>☒ CGVD2013</td>
<td>☐ Other: _________</td>
<td>☐ USGS DEM (.dem)</td>
<td>Source Data File Format</td>
</tr>
</tbody>
</table>

Geoid   | Product Units | Derived DEM File Format (extension) | Source Data File Format |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>☒ CGG2013</td>
<td>☒ Metres</td>
<td>☐ ERDAS IMG (.img)</td>
<td>☐ ASPRS .las (version______)</td>
</tr>
<tr>
<td>☐ Other: ___</td>
<td>☐ Other: ______</td>
<td>☐ ASPRS .las (ver.____)</td>
<td>☐ Other: _____________________________</td>
</tr>
</tbody>
</table>

Comments / User Waiver:

Branch representative name and signature _______________________________________________________
Supplier representative name and signature _______________________________________________________
Date and Location _______________________________________________________

Owner: GeoBC
Version Number: 2.2
Issue Date: May 2017
Title: Specifications for the Production of Digital Elevation Models for the Province of British Columbia
The following are also defaults requirements, the Branch shall document any deviations in the project specific requirements.

- Accuracy Reports shall be delivered for each dataset used as source data and for derived DEMs, using the blank forms in Appendix D. Examples with five control or verification points can be seen in Table 5 and Table 6. Definitions and equations for the terms used in the tables can be found in Appendix D and in the Glossary. Although the tables show only 5 control/verification points, a minimum of 20 points shall be used to complete the reports.

Table 5. Example of an Accuracy Report for source data

<table>
<thead>
<tr>
<th>Point ID</th>
<th>Measured Values (metres)</th>
<th>Survey Check Point Values (metres)</th>
<th>Residuals (errors) (metres)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Easting (x)</td>
<td>Northing (y)</td>
<td>Elevation (z)</td>
</tr>
<tr>
<td>GCP1</td>
<td>359584.39</td>
<td>5142449.93</td>
<td>477.13</td>
</tr>
<tr>
<td>GCP2</td>
<td>359872.19</td>
<td>5147939.18</td>
<td>412.41</td>
</tr>
<tr>
<td>GCP3</td>
<td>395893.09</td>
<td>5136979.82</td>
<td>487.29</td>
</tr>
<tr>
<td>GCP4</td>
<td>359927.19</td>
<td>5151084.13</td>
<td>393.59</td>
</tr>
<tr>
<td>GCP5</td>
<td>372737.07</td>
<td>5151676.00</td>
<td>451.31</td>
</tr>
</tbody>
</table>

Number of check points | 5 | 5 | 5
Mean Error            | -0.033 | 0.006 | 0.006
Standard Deviation    | 0.108  | 0.119 | 0.091
Root Mean Square Error RMSE, 1dRMSE at 68% Confidence Level | 0.102  | 0.106 | 0.081
Radial Horizontal Accuracy RMSER, 1dRMSER at 63% Confidence Level | 0.147
Horizontal Accuracy (ACCr) at 95% Confidence Level | 0.255
Non-vegetated Vertical Accuracy (NVA) at 95% Confidence Level | 0.160
Vegetated Vertical Accuracy (VVA) at 95th Percentile | 0.244
Table 6. Example of an Accuracy Report for DEM products

<table>
<thead>
<tr>
<th>Point ID</th>
<th>Measured Values (metres)</th>
<th>Survey Check Point Values (metres)</th>
<th>Residuals (errors) (metres)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Easting (x)</td>
<td>Northing (y)</td>
<td>Elevation (z)</td>
</tr>
<tr>
<td>VP1</td>
<td>359584.39</td>
<td>5142449.93</td>
<td>477.13</td>
</tr>
<tr>
<td>VP2</td>
<td>359872.19</td>
<td>5147939.18</td>
<td>412.41</td>
</tr>
<tr>
<td>VP3</td>
<td>395893.09</td>
<td>5136979.82</td>
<td>487.29</td>
</tr>
<tr>
<td>VP4</td>
<td>359927.19</td>
<td>5151084.13</td>
<td>393.59</td>
</tr>
<tr>
<td>VP5</td>
<td>372737.07</td>
<td>5151676.00</td>
<td>451.31</td>
</tr>
</tbody>
</table>

Number of check points | 5

Mean Error | -0.033 | 0.006 | 0.006

Standard Deviation | 0.108 | 0.119 | 0.091

Root Mean Square Error RMSE, 1dRMSE at 68% Confidence Level | 0.102 | 0.106 | 0.081

Radial Horizontal Accuracy RMSEr, 1dRMSEr at 63% Confidence Level | 0.147

Horizontal Accuracy (ACCr) at 95% Confidence Level | 0.255

Non-vegetated Vertical Accuracy (NVA) at 95% Confidence Level | 0.160

Vegetated Vertical Accuracy (VVA) at 95th Percentile | 0.244

- Void areas shall be coded using a unique “NODATA” value.
- Low Confidence Areas (ASPRS, 2014) shall not be acceptable as part of the DEMs.
- Tiled derived DEMs shall have a 100 metre buffer on the outer margins during production. The tiles shall be clipped and show a 50 metre buffer when delivered.
- DEM tiles shall have no edge artifacts or mismatch.
- Correct file naming convention shall be used as described in Appendix E.
- A quilted appearance in the overall DEM surface will be cause for rejection of the entire DEM deliverable, whether the rejection is caused by differences in processing quality or character among tiles, swaths, lifts, or other non-natural divisions.
- 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.
• 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 (FGDC, 2014) standards, per complete project dataset. 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.
9.0 REFERENCES


FGDC - Federal Geographic Data Committee. Geospatial Positioning Accuracy Standards
URL: https://www fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part3

FGDC - Federal Geographic Data Committee. “Geospatial Metadata Standards”
Internet: http://www fgdc.gov/metadata/geospatial-metadata-standards
Last Updated: Sep 12, 2014


URL: http://www.ifp.uni-stuttgart.de/publications/phow11/180Hirschmueller.pdf

ISO/TC 211 Geographic information/Geomatics Terminology; Multi-Lingual Glossary of Terms, 2015 URL: http://www.isotc211.org/Terminology.htm


Sources for the Figures:

Figure 1. Knippers, R. 2009, Geometric Aspects of mapping, 3. Reference surfaces for mapping URL: http://kartoweb.itc.nl/geometrics/reference%20surfaces/refsurf.html


Figure 5. Jedlička, K. 2009. Accuracy of surface models acquired from different sources - important information for geomorphological research. Geomorphologia Slovaca et Bohemica, 9, 1. URL: http://www.asg.sav.sk/gfsb/v091/

Figure 6. Murai, S. 1998. GIS Work Book- Fundamental Course and Technical Course, 2-8 Data Structure for Continuous Surface Model. URL: http://wtlab.iis.u-tokyo.ac.jp/~wataru/lecture/rsgis/giswb/vol1/cp2/2-11.gif

Figure 7, 8 and 9. Wikimedia Commons, Public domain (Berland) URL: https://commons.wikimedia.org/wiki/File:BicubicInterpolationExample.png
URL: https://commons.wikimedia.org/wiki/File:BilinearInterpolExample.png
URL: https://commons.wikimedia.org/wiki/File:Nearest2DInterpolExample.png

Figure 11. NOAA, 2015 - Digital Coast GeoZone; Tech talk for the Digital Coast. Considerations for Coastal Elevation Mapping URL: https://geozoneblog.wordpress.com/2015/12/14/considerations-for-coastal-elevation-mapping/
APPENDIX A HYDROLOGIC TREATMENTS

Hydro-Flattening

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 through the use of 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 (Heidermann, 2014).

Bare-earth LiDAR points that are near the breaklines shall be classified as Ignored Ground and excluded from the DEM generation process. This process prevents unnatural surface artifacts from being created between mass points and breakline vertices. The proximity threshold for reclassification as Ignored Ground is at the discretion of the data producer but will not exceed the relevant TIN Point Density listed in Table 3. Figure 11 shows an example of the effects adding breaklines can have on the aspect of the TIN. The circles show TIN artifacts.

![Figure 11. Example of breaklines used for hydro-flattening](image)

The requirements for hydro-flattening are listed below. These requirements also define the minimum features for which breaklines shall be collected and delivered.

**Inland ponds and lakes**

- Water bodies of 8,000 metres$^2$ 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 streams or rivers.

**Inland streams and rivers**

- Streams and rivers of an average 30 metres width shall be flattened and will 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 the course of the collection (such as increased upstream dam discharge) shall be documented in the project metadata.

**Tidal water bodies**

Any water body that is affected by tidal variations, including oceans, seas, gulfs, bays, inlets, salt marshes, and large lakes. Tidal variations during data collection or between different data collections will result in lateral and vertical discontinuities along shorelines. 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 planned to be done at low tide so it is as close as possible to the mean sea level and so the 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 producers 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, cooperating partners may impose additional requirements for tidal coordination.

Islands

• Permanent islands 4,000 metres² 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 relates to the adjustment of DEM surfaces for other hydrologic analyses (Maune et al., 2007). Those hydrological treatments would be project specific and the final requirements shall be determined by the Branch.

1. 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.

2. 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 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.

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. Two types of breaklines are used: sharp breakline, that causes a definite pointed character to the interpolated contour, and rounded that causes a smoother but still well defined deflection to the contour.

Breaklines deliverables shall conform to the following procedures and specifications:

• Developed to the limit of the project area, delivered in ESRI shapefile or file geodatabase formats, as PolylineZ and PolygonZ feature classes, as appropriate to the type of feature represented and the methodology used by the data producer.
• Breakline delivery may be in a single layer or in tiles, at the discretion of the data producer. In the case of tiled deliveries, all features shall edge-match exactly across tile boundaries in both the horizontal (x,y) and vertical (z) spatial dimensions.
• Same coordinate reference system and units used (horizontal and vertical) as the DEM.
• Properly formatted and accurate georeferenced information for each feature class, stored in that format’s standard file system location. Each shapefile shall include a correct and properly formatted .prj file.
• Even though the final models will not include the breaklines used to generate them, delivered data shall be sufficient to effectively re-create the delivered DEM using the source mass points and breaklines without substantial editing.
APPENDIX B ASPRS (2014) REFERENCES TABLES

Table 7 and Table 8 show the values taken from ASPRS (2014) Table B.7 and Table B.9 that were used as a reference to establish the values in Table 3.

The Branch could use these tables as a reference to demand a Quality Level with higher accuracy and resolution requirements than QL1, depending on the specific project requirements. The "DEM Grid Size" in Table 3 was established by rounding the Maximum Nominal Point Spacing (NPS) in Table 8 up to an adequate integer. For example, for a source data NPS of 0.35 metre, the gridded DEM cell size required shall be higher or equal to 0.50 metre, thus reflecting a more stringent requirement for the source data. As for the "TIN Point Density" in Table 3, it shall be higher than the Minimum Nominal Point Density (NPD) of the source data listed in Table 8.

Table 7. Quality Levels and Vertical Accuracy for Digital Elevation Data

<table>
<thead>
<tr>
<th>Quality Level</th>
<th>Vertical Accuracy Class (cm)</th>
<th>Absolute Accuracy</th>
<th>RMSE, Non-vegetated (cm)</th>
<th>NVA at 95% Confidence Level (cm)</th>
<th>VVA at 95th Percentile (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QL1</td>
<td>1.0</td>
<td></td>
<td>1.0</td>
<td>2.0</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td></td>
<td>2.5</td>
<td>4.9</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td></td>
<td>5.0</td>
<td>9.8</td>
<td>15.0</td>
</tr>
<tr>
<td>QL2</td>
<td>10.0</td>
<td></td>
<td>10.0</td>
<td>19.6</td>
<td>30.0</td>
</tr>
<tr>
<td>QL3</td>
<td>15.0</td>
<td></td>
<td>15.0</td>
<td>29.4</td>
<td>45.0</td>
</tr>
<tr>
<td></td>
<td>20.0</td>
<td></td>
<td>20.0</td>
<td>39.2</td>
<td>60.0</td>
</tr>
<tr>
<td>QL4</td>
<td>33.3</td>
<td></td>
<td>33.3</td>
<td>65.3</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>66.7</td>
<td></td>
<td>66.7</td>
<td>131</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td></td>
<td>100</td>
<td>196</td>
<td>300</td>
</tr>
<tr>
<td>QL5</td>
<td>333</td>
<td></td>
<td>333</td>
<td>653</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 8. Quality Levels, NPS and NPD for Digital Elevation Data

<table>
<thead>
<tr>
<th>Quality Level</th>
<th>Vertical Accuracy Class (cm)</th>
<th>Absolute Accuracy</th>
<th>RMSE, Non-vegetated (cm)</th>
<th>NVA at 95% Confidence Level (cm)</th>
<th>Recommended Minimum NPD (pts/m²)</th>
<th>Recommended Maximum NPS (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QL1</td>
<td>1.0</td>
<td></td>
<td>1.0</td>
<td>2.0</td>
<td>≥20</td>
<td>≤0.22</td>
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### APPENDIX C REQUIREMENTS CHECKLIST

#### User Requirements Checklist for Project:

- [ ] Quality Level 1 (QL1)
  - Model Type 1: Gridded DEM
  - Model Components 1: Bare-Earth
  - Supplemental Surface Treatments 1: Buildings Flattened

- [ ] Quality Level 2 (QL2)
  - Model Type 2: TIN
  - Model Components 2: Hydro-Flattened
  - Supplemental Surface Treatments 2: DTM Points Thinned (factor: __)

- [ ] Quality Level 3 (QL3)
  - Model Type 3: Source DTM
  - Model Components 3: Bridges Excluded
  - Supplemental Surface Treatments 3: Breaklines used for Model

- [ ] Quality Level 4 (QL4)
  - Model Type 4: Other: ______
  - Model Components 4: Roads Class. as Ground
  - Supplemental Surface Treatments 4: Other: ______________

- [ ] Quality Level 5 (QL5)
  - Model Type 5: Other: _____
  - Model Components 5: Other: ______
  - Supplemental Surface Treatments 5: Other: ______________

#### Comments / User Waiver:

- Grid Cell Size
  - ≤ 0.50
  - 1.0
  - 2.0
  - 5.0
  - ≥ 10
  - NA

- TIN Point Density
  - ≤ 0.5
  - 1.0
  - 2.0
  - ≥ 10
  - NA

- Source Data Technology
  - Stereo Imagery
  - Airborne Laser
  - Airborne Radar
  - Space-borne Radar
  - Other: ______________

- Source DTM Type
  - DTM extracted by SGM
  - Ground LiDAR DTM
  - Derived using InSAR
  - Other: ______________

#### Horizontal Datum

- NAD 83
- UTM (Zone___)

#### Vertical Datum

- bcalber

#### Geoid

- Product Units
  - Metres
  - Other: ___

#### Derived DEM File Format (extension)

- ESRI TIN (.tin)
- ESRI GRID (.asc)
- USGS DEM (.dem)
- ERDAS IMG (.img)
- ASPRS .las (version __)

#### Source Data File Format

- Source Data Technology
  - Other: ______________

#### Comments / User Waiver:

- Branch representative name and signature ________________________________

Owner: GeoBC
Version Number: 2.2
Issue Date: May 2017
Title: Specifications for the Production of Digital Elevation Models for the Province of British Columbia
APPENDIX D ACCURACY REPORTING

Table 9 and Table 10 shall be used by the data supplier to report the horizontal and vertical accuracies of the source data as well as the horizontal and vertical accuracies of the DEMs delivered. (modified from ASPRS, 2014).

Equations used to calculate the values in the reports:

Residual Errors $\Delta = \frac{\sum(N_i - N'_i)}{n}$

where:
- $N_i$ is the $i^{th}$ measured coordinate being evaluated, in the specified direction
- $N'_i$ is the corresponding check point $i^{th}$ coordinate for the points being evaluated, in the specified direction
- $i$ is an integer ranging from 1 to $n$ and
- $n$ the number of checkpoints

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

where:
- $\Delta_i$ is the $i^{th}$ residual error in the specified direction
- $i$ is an integer ranging from 1 to $n$ and
- $n$ the number of checkpoints

Standard Deviation $\sigma = \sqrt{\frac{\sum(\Delta_i - \bar{\Delta})^2}{(n-1)}}$

where:
- $\Delta_i$ is the $i^{th}$ residual error in the specified direction
- $\bar{\Delta}$ is the mean error in the specified direction
- $i$ is an integer ranging from 1 to $n$ and
- $n$ the number of checkpoints

Root Mean Square Error $\text{RMSE}_n = \sqrt{\frac{\sum(N_i - N'_i)^2}{n}}$ (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 $i^{th}$ coordinate for the points being evaluated, in the specified direction
- $i$ is an integer ranging from 1 to $n$ and
- $n$ the number of checkpoints

Radial Horizontal Accuracy $\text{RMSE}_r = \sqrt{(\text{RMSE}_x^2 + \text{RMSE}_y^2)}$ (1dRMSE, at 63% probability)

where:
- $\text{RMSE}_x$ is the RMSE in the $x$ direction, and
- $\text{RMSE}_y$ is the RMSE in the $y$ direction

Horizontal Accuracy $\text{ACC}_r = \text{RMSE}_r \times 1.73$ (at 95% Confidence Level)

Non-vegetated Vertical Accuracy $\text{NVA} = \text{RMSE}_z \times 1.96$ (at 95% Confidence Level)

Vegetated Vertical Accuracy $\text{VVA} = \text{RMSE}_z \times 3.00$ (at 95th Percentile)
<table>
<thead>
<tr>
<th>Point ID</th>
<th>Measured Values (metres)</th>
<th>Survey Check Point Values (metres)</th>
<th>Residuals (errors) (metres)</th>
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<td>Northing (y)</td>
<td>Elevation (z)</td>
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<tr>
<td>Horizontal Accuracy (ACCr) at 95% Confidence Level</td>
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<tr>
<td>Non-vegetated Vertical Accuracy (NVA) at 95% Confidence Level</td>
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<tr>
<td>Vegetated Vertical Accuracy (VVA) at 95th Percentile</td>
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Table 10. Accuracy Report for DEM Products

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<th>Point ID</th>
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<th>Survey Check Point Values (metres)</th>
<th>Residuals (errors) (metres)</th>
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<th>Standard Deviation</th>
<th>Root Mean Square Error RMSE, 1dRMSE at 68% Confidence Level</th>
<th>Radial Horizontal Accuracy RMSEr, 1dRMSEr at 63% Confidence Level</th>
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Owner: GeoBC
Title: Specifications for the Production of Digital Elevation Models for the Province of British Columbia
Version Number: 2.2
Issue Date: May 2017
APPENDIX E FILES NAMING CONVENTIONS

For DEM products delivered in LAS (.las) file format:

(Ownership)_(Geographic Extent)_x(Classification)_ (Minimum Shot Density)_ (Projection)_ (Date).las

Ownership = GeoBC (i.e. bc_)
Geographic Extent = Geographic BC Map tile
Classification = yes or no
Point Density = points per square metre, shall be an integer number (i.e. 5) or a decimal number denoted by ‘p’ (i.e. 7p03)
Projection = projection used
Date = submission of file by year-month-day in 6-digit form

e.g. bc_0921081_1_1_3_xyes_31_utm_150105.las

For DEM products delivered in other file formats:

(Ownership)_(Geographic Extent)_(Acquisition Type)(Grid Size)_ (Projection)_ (Year of Photography)_(file type)

Ownership = GeoBC (i.e. bc_)
Geographic Extent = Geographic BC Map tile
Acquisition Type = l for LiDAR, r for Radar, and rgbir for Photogrammetric
Grid Size = cell size in metres, shall be an integer number (i.e. 2m) or a decimal number denoted by ‘p’ (i.e. 2p5m)
Projection = Map projection (i.e. bcalber for BC Albers, or utm10 for Universal Transverse Mercator zone 10 North)
Year of Photography = Year-Month-Day in 6-digit format

e.g. bc_092o015_xrgbir2m_utm10_141123.dem

Notes:

1. There shall be no capital letters, dashes, spaces or special characters in ANY file names because those will cause problems in the warehouse catalogue and in the BMOS (formerly IDT).

2. There is considerable variation in satellite file names depending on the metadata of the imagery, but they mostly follow the same basic framework.
LIST OF ACRONYMS

1dRMS  One distance root mean square error
2dRMS  Two distance root mean square error
ACCr   Radial Accuracy (NSSDA)
AGL    Aircraft altitude above ground level at Nadir position
ASPRS  American Society for Photogrammetry and Remote Sensing
AT     Aerial Triangulation
DEM    Digital Elevation Model
DSM    Digital Surface Model
DTM    Digital Terrain Model
FGDC   Federal Geographic Data Committee
GPS    Global Positioning System
GSD    Ground Surface Distance
IMU    Inertial Measurement Unit
INS    Inertial Navigation System
InSAR  Interferometric Synthetic Aperture Radar
LiDAR  Light Detection And Ranging
NDEP   National Digital Elevation Program
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
RMSEr  Horizontal root mean square error (radial)
RMSEx  Horizontal (x) Root Mean Squared Error
RMSEy  Horizontal (y) Root Mean Squared Error
RMSEz  Vertical (z) Root Mean Squared 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

**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.

**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 AGL is the aircraft altitude above ground level at Nadir position. In this context, the altitude is defined as a height measured with respect to the underlying ground surface, meaning above mean sea level.

**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 manmade 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.

**Checkpoint (check point)** - A surveyed point used to estimate the positional accuracy of a geospatial dataset against an independent source of greater accuracy. Checkpoints are independent from, and may never be used as, control points on the same project.
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 manmade 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, checkpoints on the same project.

Coordinates - A group of 3D numbers that define a point in 3D space. 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 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 manmade 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 Models (DSMs) – 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 3-dimensional 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 – Geopositioning an object using a Correspondence Model derived from a set of points for which both ground and image coordinates are known.

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 considered to be 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.

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 camera height above average horizontal terrain.

Horizontal 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. In traditional maps that are compiled photogrammetrically, this process is accomplished automatically through the inclusion of measured breaklines in the digital terrain model however, because mass points do not inherently include breaklines, a DEM or TIN derived solely from mass points will depict water surfaces with unsightly and unnatural artifacts of triangulation. The process of hydro-flattening typically involves the addition of breaklines along the banks of specified 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.

Inertial Measurement Unit (IMU) – The combination of a 3-axis accelerometer combined with a 3-axis gyro. 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, in opposition to the INS (Inertial Navigation System), which integrate the measurements of its internal IMU to provide a navigation solution. For instance, an Inertial Navigation System (INS) uses an IMU to form a self-contained navigation system which uses measurements provided by the IMU to track the position, velocity, and orientation of an object relative to a starting point, orientation, and velocity.

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 gyro drift.
**Intensity (LiDAR)** - For discrete-return LiDAR instruments, intensity is the recorded amplitude of the reflected LiDAR pulse at the moment the reflection is captured as a return by the LiDAR instrument. LiDAR intensity values can be affected by many factors such as the instantaneous setting of the instrument’s Automatic Gain Control and angle of incidence and 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 colorized to measure elevation or changes in the topography on the earth's surface.

**Interpolation** - Procedure used to estimate the z-values at a point with x/y coordinates at locations lacking sampled points and is based on the principles of spatial autocorrelation, which assumes that closer points are more similar compared to farther ones.

**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 point location of the reflecting target’s 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 in those areas.

**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 (FGDC) metadata), reports (collection, processing, Quality Assurance/QA/ QC), and other supporting data (for example, survey points, shapefiles).

**Model** - Abstraction 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 metre (pl/m²). 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. Assuming metres are being used in both expressions, NPD can be calculated from NPS using the formula:

$$NPD = \frac{1}{NPS^2}$$

**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. Assuming metres are being used in both expressions, NPS can be calculated from Nominal Point Density (NPD) using the formula:

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

**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 or irrelevant or meaningless cells that exist due to poor scanning or imperfections in the original source document.

**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:

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

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 95th percentile),
- \(N\) is the number of observations in the sample data set.

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

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

where:

- \(Q_p\) 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 - Vehicles that are free to operate in three dimensions, such as an aircraft, can change their attitude and rotation about the three orthogonal axes centered on the vehicle’s center of gravity — the longitudinal, vertical, and horizontal 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.

Plumbline - 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. Related to the source data and DEM products quality.

**Projected coordinate reference system** - A method used to represent the curved, 3D surface 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 fulfills 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 insure 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)** - The National Standards for Spatial Data Accuracy (NSSDA) (Federal Geographic Data Committee, 1998) reporting standard in the horizontal component that equals the radius of a circle of uncertainty, such that the true or theoretical horizontal location of the point falls within that circle 95 percent of the time. \( \text{ACCr} = 1.7308 \times \text{RMSEr} \)

**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** - Set of regularly spaced, continuous cells with, in the case here, bare-earth elevation values attached to the center of each cell and the value for a cell is assumed to be valid for the whole cell area.

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

**Roll** - Vehicles that are free to operate in three dimensions, such as an aircraft, can change their attitude and rotation about the three orthogonal axes centered on the vehicle’s center of gravity – the longitudinal, vertical, and horizontal 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 (RMSEx and RMSESy) and vertical (RMSEz) coordinates where standard or accepted values are known, as with GPS-surveyed checkpoints of higher accuracy than the data being tested.

The standard equations for calculating horizontal and vertical RMSE are provided.
RMSE\textsubscript{x} The horizontal root mean square error in the x direction (easting):
\[ \sqrt{\frac{\sum (X_i - X'_i)^2}{n}} \]

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\textsubscript{y} The horizontal root mean square error in the y direction (northing):
\[ \sqrt{\frac{\sum (Y_i - Y'_i)^2}{n}} \]

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\textsubscript{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\textsubscript{x} is the RMSE in the x direction, and
RMSE\textsubscript{y} is the RMSE in the y direction.

RMSE\textsubscript{z} The vertical root mean square error in the z direction (elevation):
\[ \sqrt{\frac{\sum (Z_i - Z'_i)^2}{n}} \]

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 offer a good mixture of speed, quality and robustness. On the other hand, that 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 Networks (TINs)** - 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 neighbours. 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 are able to capture critical points that define terrain discontinuities and are topologically encoded so that adjacency and proximity analyses can be performed. TINs have several other advantages over gridded DEMs but they are probably best known for their superiority in surface modeling.

**yaw** - Vehicles that are free to operate in three dimensions, such as an aircraft, can change their attitude and rotation about the three orthogonal axes centered on the vehicle’s center of gravity – the longitudinal, vertical, and horizontal axes. Motion about the perpendicular 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.)
LIST OF FIGURES

Figure 1. Height Types ................................................................. 6
Figure 2. Example of a Point Cloud DSM, from LiDAR ......................... 7
Figure 3. Example of a Point Cloud DSM, generated using SGM ............. 7
Figure 4. Typical Data Flow from DSM to derived products .................... 8
Figure 5. Differences between a Raster and a Lattice ............................ 9
Figure 6. Gridded DEM and TIN ...................................................... 10
Figure 7. Example of the result of bicubic interpolation .......................... 11
Figure 8. Example of the result of bilinear interpolation ......................... 12
Figure 9. Example of the result of nearest-neighbour interpolation ............ 12
Figure 10. General production steps for LiDAR for DTM generation .......... 16
Figure 11. Example of breaklines used for hydro-flattening .................... 29

LIST OF TABLES

Table 1. Comparison of model types .............................................. 13
Table 2. Comparison between LiDAR derived DSMs and SGM derived DSMs ...... 17
Table 3. Requirements per Quality Level ........................................ 21
Table 4. Example of a User Requirement Checklist with defaults requirements .... 23
Table 5. Example of an Accuracy Report for source data ........................ 24
Table 6. Example of an Accuracy Report for DEM products .................... 25
Table 7. Quality Levels and Vertical Accuracy for Digital Elevation Data ...... 33
Table 8. Quality Levels, NPS and NPD for Digital Elevation Data ............... 33
Table 9. Accuracy Report for Source Data ....................................... 37
Table 10. Accuracy Report for DEM Products .................................... 38