Specifications for LiDAR for the Province of British Columbia

Ministry of Forest, Lands and
Natural Resources Operations GeoBC

Version 3.0, March 2017
Victoria (BC), Canada

Table of Contents

1.0 RECORD OF AMENDMENTS

Version No.	Revision made by	Page#	Revision Description	Approved by	Signature	Date
1.0	Harald Steiner	1-36	Re-write	Harald Steiner, Geom Eng		31-Mar-2013
2.0	D. Garnham	1-40	Major revision of 1.0	Harald Steiner, PEng		21-Mar-2014
3.0	Isabelle Paquin Brett Edwards James Thompson Robert Prins	1-42	Revision to align with GeoBC 2016 DEM specifications	Harald Steiner, PEng		04-Oct-2016

2.0 INTRODUCTION

These specifications were compiled to provide geospatial data suppliers with some common standard and clear requirements for the production of LiDAR datasets, with the objective of obtaining consistent, high-quality LiDAR products deliverables to the British Columbia Provincial Government.

These LiDAR specifications supersede all previous LiDAR specifications. One should note that this document is a living one, and it will be updated and maintained through the ongoing feedback from industry experts and advances in the LiDAR technology processing methodologies.

The term “Branch”, when used herein, shall mean GeoBC of the Ministry of Forests, Lands and Natural Resource Operations in the Province of British Columbia.

The Branch shall be the final authority on acceptance or rejection of submitted LiDAR data. All LiDAR material, data and products delivered to the Branch shall meet or exceed the following specifications.

For the purpose of these specifications, the word “shall” indicates a mandatory requirement and “should” indicates a desirable requirement.

3.0 PURPOSE AND SCOPE

This document has been created to outline clear specifications for the support of Quality Assurance (QA) and Quality Control (QC) of LiDAR data and subsystems. This document is not meant to be prescriptive but does describe desired results and tolerances. More precisely, the purpose of these specifications are to:

- Focus on results, not on how a system should be calibrated.
- Provide minimum standards regarding accuracy, deliverables, and quality.
- Ensure proper and consistent deliverables.
- Ensure a high level of data integrity.

4.0 LiDAR BACKGROUND

Mobile LiDAR acquisition modes are of three main types:

- Airborne LiDAR scanning (ALS): scanning with a LiDAR scanner mounted to a platform in an aircraft (rotor or fixed-wing aircraft).
- Mobile LiDAR scanning (MLS): scanning from a ground-based mobile vehicle.
- Unmanned LiDAR scanning (ULS): scanner mounted on an Unmanned Aerial Vehicle (UAV).

The specifications detailed in this document are applicable primarily to ALS.

A Light Detection and Ranging (LiDAR) system consists of the following components:

- An inertial navigational measurement unit (IMU) continuously recording the aircraft's orientation (attitude vectors).
- A high-precision Global Positioning System (GPS) unit recording the three-dimensional position of the aircraft.
- A computer interface managing communication between devices and data storage during acquisition.

The system also necessitates that a GPS base station is operating simultaneously to correct differentially and improve the precision of the collected airborne GPS data. That base station is typically installed at a known location on the ground and in the vicinity (within 30-50 kilometres) of the aircraft.

LiDAR systems are a fast, accurate, and cost-effective technology for direct acquisition of small or large-scale, dense 3D-point data. LiDAR data is visualised as a point cloud collected by measuring the time between the emission of a laser pulse and the return of the reflected energy to the laser receiver.

The time between transmission and receiving of a laser return is converted to a distance and integrated with the platform position and orientation to obtain real-world coordinates. Those world coordinates are transformed into projected map coordinates. After georeferencing the data, the LiDAR points and associated metadata are exported into manageable data files, suitable for conversion to a format such as LAS using the appropriate ASPRS LAS standard.

LiDAR data consist of irregularly spaced points and attribute information that includes position, assigned colour, time stamp and other additional records about the laser return. This process requires a different data container when compared to regular digital imagery raster data. Also, the LAS format can host additional information such as spectral encoded RGB colour information of digital imagery.

There are two types of LiDAR acquisition; these are differentiated by how backscattered laser energy is quantified and recorded by the sensor. With full-waveform LiDAR (e.g., ASPRS LAS version 1.4 [2]), the energy reflected back to the sensor is logged as a nearly continuous signal. With discrete-return or small-footprint LiDAR (e.g., ASPRS LAS version 1.2 [1]), the energy reflected is recorded at precisely referenced points in space (x, y, z coordinates) and time, at amplitude intervals. The energy amplitude relating to each return is known as intensity.

Unless specified otherwise in the contract, LiDAR data shall be delivered in LAS 1.2 format, following the "LAS Specification Version 1.2 (2008)" requirements. Other LiDAR format, such as LAS 1.4, might be used if allowed in the User Requirements Checklist, in which case the requirements of the "LAS Specification Version 1.4–R13 (2013)" shall be followed. However, the specifications described in this document do not detail deliverables on full-waveform LiDAR.

Before performing data analysis towards generating any deliverable, the integrity of the dataset must be validated. This validation includes verifying that the absolute and relative accuracy of the point cloud is as expected. The contributing factors and associated processes will be discussed in detail later in this document.

After having validated the data integrity, the data goes through a series of steps that vary between providers but are similar in their goals. These steps take the data from calibrated, unclassified data to the desired deliverable. There is considerable room for ambiguity in specifying deliverables, so it is essential to be as explicit as possible about the final deliverable requirements before data collection.

LiDAR datasets are usually large, and file sizes will vary according to point density, information stored within each file, and total area covered per file. A LAS 1.2 file covering 1 Km^2, with an average total density of $\leq$1 point per square metre can be approximately 60MB (uncompressed) depending on format type and number of returns. Typically, LiDAR datasets are broken down into file sizes that can be easily manipulated on a high-end processing workstation using specialised tools.

One of the inherent problems with LiDAR data is that individual LiDAR returns cannot be directly associated with a feature, this means that trying to analyse unclassified LiDAR data points will yield little useful information. It is only by analysing groups of LiDAR points together that context is achieved, and individual points can be grouped into categories according to recognisable features. The easiest way to do this is to group the LiDAR data into distinct feature classes based on the ASPRS Standard LiDAR point class structure. It is also important to note that LiDAR data providers will often have widely varying standards and definitions with regards to how LiDAR classes are derived. It is in the best interest of the Branch to provide a common set of standards to ensure uniform data quality and a standardised data format.

5.0 ACQUISITION AND QUALITY ASSURANCE

Quality Assurance (QA) is a set of activities that ensure quality in the processes by which products are developed. In particular, the measures that are taken to ensure the quality of the source data, before and during the acquisition of the data.

5.1 LiDAR Error Budget

LiDAR errors are categorised into random and systematic components. Systematic errors in the data can be reconciled and possibly reduced or eliminated through calibration and adjustment, whereas random errors cannot. All LiDAR system malfunctions shall be recorded, and the Branch shall be notified. A malfunction is defined as a failure anywhere in the acquisition platform units that causes an interruption to the normal operation of the system.

5.1.1 Systematic Errors

Systematic biases in the system measurements, mirror angle measurements, measured ranges, and calibration parameters (e.g., boresighting parameters relating the system components) will lead to systematic errors in the derived point cloud.

The following list and Table 1 gives some diagnostic hints about the impact of systematic biases in the system measurements and calibration parameters on the derived point cloud. All systematic errors shall be accounted for and reconciled by the data provider before delivery.

- Boresighting Offset Bias (spatial offset between the laser beam firing point and the GPS/IMU unit) would lead to a constant shift in the object space assuming constant attitude. The magnitude of the introduced shift is independent of the system parameters (flying height and look angle). However, the components of the impact in the horizontal directions are affected by the flight direction.
- Angular Biases (IMU or mirror angles) would affect the horizontal coordinates more than the vertical coordinates. The magnitude and components of the impact depend on the system parameters (flying height and look angle).
- Laser Beam Range Bias will mainly affect the vertical more than the horizontal coordinates. The effect will be independent of the system flying height. However, it will depend on the system look angle (i.e., the magnitudes of the impact in the nadir and off-nadir regions will be different).
- Atmospheric Propagation (Harry will give info).

Table 1. Summary of the systematic biases and their impact

	Flying Height	**Flying Direction**	**Look Angle**
Boresighting Offset Bias	Effect is independent of flying height	Effect is dependent on the flying direction (except D_Z)	Effect is independent of the look angle
Boresighting Angular Bias	Effect increases with flying height	Effect changes with the flying direction	Effect changes with the look angle (Except D_X)
Laser Beam Angular Bias	Effect increases with the flying height	Effect changes with the flying direction (except D_Y)	Effect changes with the look angle (Except D_X)
Laser Beam Range Bias	Effect is independent of flying height	Effect is independent of flying direction	Effect depends on the look angle (Except D_Y)
Atmospheric Propagation	Effect is independent of flying height	Effect is independent of flying direction	harry

The table assumes a linear scanner flying over a flat horizontal terrain along a straight line trajectory with a constant attitude along the y-direction.

5.1.2 Random Errors

Random errors comprise the remaining errors after all systematic errors have been accounted for and corrected. Random errors might occur in the dataset as random noise or false-positive LiDAR returns that will be apparent when points are very high or much lower than the collected data. All random error points shall be classified using the "Withheld Point" class code (Section 6.3) before processing the deliverables because they can significantly skew statistical data and interfere with certain classification algorithms. Care should be taken not to remove legitimate LiDAR returns accidentally when using automatic classification routines for extracting erroneous points.

5.2 Calibration and Data Adjustments

Sensor calibration and maintenance shall be performed to ensure proper function of the LiDAR system. Any requests by the Branch to submit evidence that the sensor system was calibrated before the project began to identify and correct systematic errors, shall be met.

5.2.1 System Calibration

Calibration, when applied to a LiDAR acquisition system, refers to the process of identifying and correcting for systematic errors in hardware, software and/or procedures. Sensors shall be calibrated for geometry and intensity.

- Instrument calibration: Factory calibration includes radiometric and geometric calibration unique to each manufacturer's hardware, and tuned to meet the performance specifications for the model being calibrated. Instrument calibration can only be assessed and corrected by the factory.
- Data calibration (boresight calibration): The lever arm calibration determines the IMU to GPS antenna phase centre and sensor to IMU (rGPS and rIMU in Figure 1) offset vectors components relative to the antenna phase centre. The offset vectors components shall be re-determined each time the sensor or aircraft GPS antenna is moved or repositioned in any way.

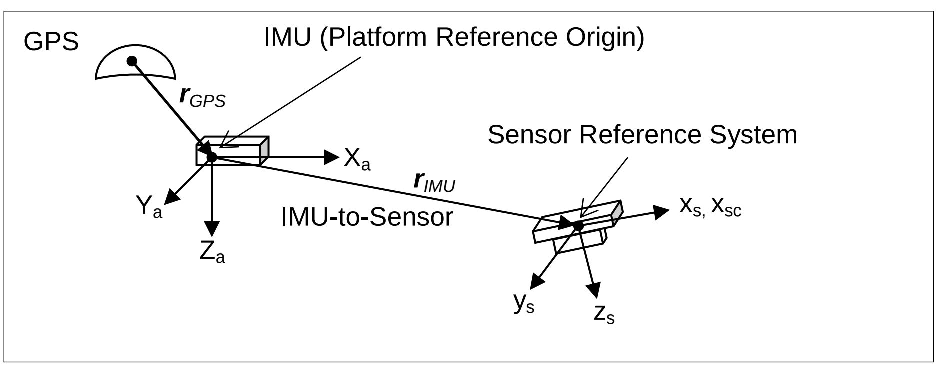

Figure 1. Relationships between the lever arms of an airborne LiDAR platform.

Because normal aircraft operations can induce slight variations in component mounting, boresight calibration shall be performed at least twice during each project, at the beginning and the end of a project. This verification allows determining the corrections to the roll, pitch, yaw, and scale calibration parameters, even if the sensor or antenna were not moved. If any modifications are made to any of the calibration parameters (including sensors), the supplier shall provide a post, re-calibration control report along with the pre-calibration control report.

Calibration done in the field should include different planes, not only flat surfaces. For examples, targets could be positioned on an inclined, non-vegetated and smooth surfaces, like a road going uphill and downhill, in addition to flat surfaces.

Report of calibration containing the values used, including all factory settings as well as user settings, shall be delivered. Additional calibration parameters may be requested by the Branch.

5.2.2 Data Adjustments

After having reconciled the systematic errors, the dataset may still contain artefacts related to flight-line overlap or adjustments to a particular local datum, geoid or other changes using least squares adjustment tools and transformations.

A high-level overview of the steps performed to arrive at final positioning should be provided with the delivery, with an output report describing the methodology and software used, and including all results.

5.2.3 Ground Control Points

All aerial LiDAR survey missions are required to be supported by a network of GPS base stations. This is essential for ensuring the absolute accuracy of the LiDAR point cloud. A GPS network that fulfils the minimum accuracy requirements shall include:

- At least one fixed control point (e.g., high precision survey monuments, active control stations, etc.). Additional fixed control points are desirable.
- At least one GPS network point used for processing flight trajectories. This may also be used as a vertical checkpoint for the LiDAR dataset.
- At least one additional GPS point must be established and observed simultaneously in order to close the loop, creating two independent baselines. This shall be used as a vertical checkpoint for the LiDAR dataset.
- Baselines should not exceed 30km in length.

The amount of GPS base stations will depend largely on the size and location of the project site. It is recommended that an additional LiDAR checkpoint be established that is tied into the network. This is crucial in situations where the GPS station that is to be used for processing trajectories is not within the project site and therefore is not available for use as a LiDAR checkpoint. It is encouraged that additional control is collected to create a robust ground control network, ensuring the geometric quality of the network and the point cloud. Unless specified otherwise in the contract, a minimum of ten control points distributed over the entire area shall be used, and should include inclined planes and cover different aspects, not only flat surfaces.

The distance between a GPS base station used in processing trajectories and the aircraft should not exceed 50km in open terrain and 30km in mountainous terrain. This assures optimal processing of trajectories and gives confidence to the geometric quality of the point cloud. If longer baselines are observed due to mitigating circumstances, it may be required that final trajectories are processed once precise ephemerides are available. For GPS survey best practices, please refer to the "Specifications and Guidelines for Control Surveys Using GPS Technology (2010)"[14].

5.3 LiDAR Acquisition Guidelines

Flight planning and hardware specifics are left to the data provider, as long as they meet the requirements and standards, and complete all relevant reports. However, all pre-acquisition plans shall be completed and submitted before acquisition start. The proposed flight plan covering the geographic area to be surveyed shall be defined as a set of flight lines declared with planned flight line overlap and include the expected buffer zone (Section 5.4). Plans shall be provided as MicroStation V8 DGN files and as ESRI SHP files.

Flying height is defined as the aircraft altitude above ground level, at nadir position, and is a function of the area to be covered in a single pass and minimum flying height safety protocols. In some cases, where there are supporting sensor requirements such as aerial photography for producing rectified imagery, more than one pass may be required to capture data within the desired parameters. Keeping a constant flying height above ground reduces systematic errors that are difficult to detect such as laser range scale errors.

The required overlap between flight lines shall be planned at 30% minimum in open urban areas and 50% minimum in vegetated areas. The bank angle must be kept at 15° maximum (absolute maximum 20°) unless the safety of the aircraft is affected.

In addition to the flight plans and general acquisition information, the system specifications and operation parameters shall be documented and also submitted to the Branch (Section 8.3).

5.4 Spatial Distribution and Area Coverage

The projected collection area, i.e., the Area of Interest (AOI), shall be buffered by a minimum of one-half swath outside of the AOI borders to create a Buffered Project Area (BPA). Ideally, a flight line centre should be positioned on the AOI border before drawing additional flight lines. Data collection is obligatory for the full extent of the BPA, and all products shall be generated to the full extent of the BPA. However, data and products in the buffer area (the area between the AOI and the BPA) will not be tested for any of the quality requirement. Control points used for QA may be located in the buffer; verification points used for QC shall not be found in the buffered area.

5.4.1 Data Spatial Regularity

The spatial distribution of geometrically usable points should be uniform and regular. Although LiDAR instruments do not typically produce regularly gridded points, collections shall be planned and executed to generate a first return point cloud approaching a regular lattice of points.

The regularity of the point pattern and density throughout the dataset should be assessed by using a method similar to the following steps, using first return points:

- Generate a density grid from the ground data with cell sizes equal to twice the required LiDAR Nominal Point Spacing (NPS) and a radius equal to the required NPS (Section 7.2.2).
- Ensure that 90% of the cells in the grid contain at least one usable LiDAR point, using single swaths, with only the first return points located within the geometrically usable centre part (typically 95%) of each swath.
- Exclude acceptable data voids (Section 5.4.3).

5.4.2 Area Coverage

A coverage check shall be performed by loading the cumulatively acquired LiDAR dataset, along with the BPA, into one of the many software packages available for such projects. The data shall be examined to check the area’s coverage, gaps between flight lines and holes or other abnormalities caused by sensor errors.

The coverage check shall be done daily in the field and again before the plane leaves the surveyed area to ensure all flight lines are covered, including adequate swath overlap. That way, if a problem is found, a reflight can be completed without the cost of remobilizing the plane.

5.4.3 Data Voids

Data voids covering areas larger than 4 x NPS^2 for single swaths, first returns points, are not acceptable, except where caused by:

- Water bodies and other areas of little Near Infra-Red (NIR) reflectivity such as dark tar-asphalted surfaces.
- Object shadowing (e.g., buildings, towers, vertical cliffs) unless previously stipulated in the project contract that all shadowed areas must be captured with subsequent flight lines.

6.0 DATA PROCESSING AND FORMATTING

The next steps in the process after acquisition and QA are classifying and tiling the LiDAR points. The main delivery of LiDAR data is the original point cloud, in LAS format. After completing QC on the final data (Section 7.0), the other required deliverables and reports can be compiled (Section 8.0)

6.1 Scope of Collection

All collected swaths, including calibration swaths and cross-ties and all collected returns within each swath, shall be delivered as part of the final deliverables. No original points are to be deleted from the LAS files. Exceptions to this rule are the extra data outside of the AOI (such as aircraft turns, transit between the collection area and airport, and transit between fill-in areas). These points may be permanently removed from the data delivered as are the swaths that are being completely discarded by the vendor and reflown.

6.2 Data Format

All processing will be carried out with the understanding that all point deliverables are required to be fully compliant with the appropriate ASPRS LAS Specification. Unless specified otherwise in the project checklist, LiDAR data shall be delivered in LAS 1.2 (ASPRS, 2008)[1]. The intensity value is the numeral representation of the pulse return magnitude and shall always be included for each discrete return. Intensity shall be normalised to a 16-bit, unsigned value.

6.3 Point Cloud Classification

Table 2 is modified from the "ASPRS Standard LiDAR Point Classes" and list the basic Class Codes that shall be used for LiDAR classification. Those codes are part of the Project checklist and can be customised to add other codes, as needed.

Outliers, noise points, geometrically unreliable points near the extreme edge of the swath, and other points the vendor deems unusable shall be identified using Class Code 7 (Withheld Point). This classification applies primarily to points that are identified during pre-processing or through automated post-processing routines or to noise points subsequently identified during manual classification or QA/QC.

Table 2. Classification Codes and Description

Class Code	Abbr.	Description
0	RAW	Created, never classified (raw data)
1	DEF	Default class, unclassified
2	GRD	Ground
3	LVG	Low Vegetation (< 0.3 metre)
4	MVG	Medium Vegetation (0.3-1 metre)
5	HVG	High Vegetation (> 1 metre)
6	BLD	Building
7	WHD	Withheld Point / Noise
8	MKP	Model Key Point
9	WTR	Water Body
10	RR	Railroad
11	PRD	Paved Road
12	--	Reserved (Overlap)
13	UPR	Unpaved Road
14	PKG	Parking
15	DRW	Driveway
16	BDG	Bridge Deck
17	MSC	All Miscellaneous
18	MSP	Miscellaneous Permanent
19	MST	Miscellaneous Temporary
20 to 31	--	Other Project specific codes

If overlap points are required to be differentiated by the data producer, they must be identified using a method that does not interfere with their classification. The technique used to identify overlap must be clearly described in the project reports.

Further instructions regarding classification:

- ALL points not classified as Withheld Point shall be classified.
- No points in the LAS deliverable shall remain in Class Code 0 or 1.
- Depending on the project requirements, the Class Code 2 (Ground) may include other flat surfaces (e.g., Roads, Parking lots, Bridge decks) instead of classifying them separately, in which case it would be indicated in the User Requirements Checklist.
- If only Ground and non-ground classes are needed, use the Class Code 17 (All Miscellaneous) to classify non-ground points that are not classified as Withheld Point.
- The Class Code 18 (Miscellaneous Permanent) include all man-made objects or structures that are not mobile and do not belong in any other Class Code (e.g., electrical or telecommunication structures, billboards, fences,

swimming pools, sheds).

- The Class Code 19 (Miscellaneous Temporary) include all mobile objects that do not belong to any other classes (e.g., cars, livestock, garbage bins, people, mailboxes).
- All planimetric shapefiles used to classify areas such as roads or water bodies shall be included in the deliverables.

6.4 Tiling

A single project tiling scheme, with no overlap, shall be agreed upon by the data producer and the Branch before collection. This tiling scheme shall respect the Branch name convention and be used for ALL tiled deliverables (Appendix B).

- Tiles shall be sized using the same units as the coordinate system of the data specified in the User Requirements Checklist.
- Tiles are required to be indexed in X and Y to an integer multiple of the tile's X-Y dimensions.
- Tiled deliverables will edge-match seamlessly and without gaps.

When classifying LiDAR in tiles, overlap shall be incorporated whenever classifying ground routines to ensure no errors generated at the edge of the tile are included in that tile. In other words, if running a ground detection routine on a tile, an additional 10 metres of data should be temporarily referenced from adjacent tiles so any errors introduced at the edge of the tile will not be part of the original tile. LiDAR data referenced from adjacent tiles shall not be saved as part of the original tile.

LAS files shall be tiled using a tiling scheme that ensures the largest file size will not be greater than 2 gigabytes. The Branch reserve the right to amend this requirement in the User Requirements Checklist.

6.5 Data Handling and Shipping

Data shall be delivered on one or more hard drives, no less than 1 TB (USB 3.0) unless specified in the project contract. Submitted storage devices shall be labelled with job number/name, collection dates of contained data (in Julian date format) and a description of contents. Data may be compressed using LAZ format. Unless stated in the contract, projects consisting of several individual areas need to be broken down and submitted into area specific directories containing LiDAR data submissions.

Data must be shipped via courier to the address specified in the contract. Allowances shall be made to ensure that data arrives on or before the delivery date specified. The data provider shall notify the Branch that the data has been sent, along with the contents of the shipment, any associated tracking number(s) and/or a faxed or digital copy of the shipping confirmation.

7.0 QUALITY CONTROL AND ACCURACY REPORTING

Quality Control (QC) provides routines and consistent checks to ensure data integrity, correctness, and completeness. Before compiling the deliverables, the absolute and relative accuracy of the LiDAR data as well as the ground data density and spacing shall be verified.

The Branch requires the QC of LiDAR data to be evenly assessed over the entire project area. For every project, the Branch will specify which of the five Quality Levels (QL) requirements the supplier shall adhere to concerning the LiDAR data. QL1 requires the highest accuracy and resolution requirements while QL5 requires the lowest.

The values listed in Table 3 for each QL are defined as follow:

- Vertical Accuracy -> Required Maximum non-vegetated elevation Root Mean Squared Error (1dRMSEz) relating to the measures done on the LiDAR ground points and reported at 68% Confidence Level (CL).
- Nominal Point Density (NPD) for ground LiDAR data (minimum)
- Nominal Point Spacing (NPS) for ground LiDAR data (maximum)

Table 3. Requirements per Quality Level

Quality Level	Vertical Accuracy 1dRMSE at 68% CL	NPD Ground LiDAR (point/m^2)	NPS Ground LiDAR (m)
QL1	≤ 5.0 cm	> 8	≤ 0.50
QL2	≤ 10 cm	> 2	1.0
QL3	≤ 20 cm	> 0.5	2.0
QL4	≤ 1.0 m	> 0.05	5.0
QL5	≤ 3.0 m	> 0.01	≥ 10

7.1 Absolute Vertical Accuracy: Methodology and Requirements

The absolute vertical accuracy of the LiDAR data shall be assessed and reported in accordance with the USGS LiDAR specifications (Heidemann, 2014)[9]. The orthometric height shall be used, i.e., above the geoid as measured along the plumb line between the geoid and a point taken upward from the geoid on the Earth’s surface.

The required vertical Root Mean Squared Errors (1dRMSEz) applies to the measures done on the LiDAR point cloud, reported at 68% Confidence Level (CL). The measures shall be done on the ground LiDAR points only, by comparing checkpoints surveyed in clear, open, nonvegetated areas (which ideally produce only single LiDAR returns) and a planar surface derived from the single return LiDAR points in those areas, such as a bare-earth Triangular Irregular Network (TIN).

The results of those measurements shall be used to complete the Accuracy Report for absolute accuracies. An example of the report is shown in the deliverables section (Appendix A).

7.2 Point Density and Point Spacing

Ability to meet density and spatial distribution requirements at particular flying heights is part of the planning process hardware settings and should allow collection of data within specified parameters. Merging of flight lines are permitted to reach point density, as long as all precision/accuracy requirements are met, but no thinning of LiDAR datasets is allowed.

7.2.1 Nominal Point Density

Nominal Point Density (NPD) as defined by the Branch refers specifically to the number of LiDAR single returns (typically last) from ground points only, per square unit of measurement (point/m^2). Assessment of the point density will be made based on a random sampling of areas, 65% of which shall contain a point count greater than or equal to the point density requirements listed in Table 3, for the QL assigned to the project.

7.2.2 Nominal Point Spacing

Nominal Point Spacing (NPS) is the spatial distribution is the measurement between adjacent ground points, in metres. Given the irregular nature of LiDAR returns it is nearly impossible to find a point that is equidistant from all other surrounding points so spatial distribution should be represented as an average. Therefore, when calculating average point spacing, it is necessary to measure between points across (along the scanner swath) and along (between the scanner swaths) the flight path. Measuring point spacing only at the centre of the swath is not an acceptable method for measuring the NPS. The point spacing shall comply with the requirements listed in Table 3, for the QL assigned to the project.

7.3 Relative Accuracy: Methodology and Requirements

Relative accuracy refers to the precision of the measurements, i.e., the ability to place an object in the same location given multiple flight lines, GPS conditions, and aircraft attitudes. The relative accuracy focuses on checking flight lines on vertical offsets, regardless of surveyed ground control points. Two primary factors need to be considered when testing LiDAR data relative accuracy.

- Smooth surface repeatability (intraswath) tested by comparing the points within an individual flight line.
- Overlap consistency (interswath) tested by comparing the points of a flight line with adjacent flight lines, in overlapping regions.

7.3.1 Intraswath accuracy

Smooth surface repeatability is a measure of variations (noise) documented on a surface that would be expected, ideally, to be flat and without variation.

Single-swath, single return data shall be:

- Assessed using only single returns in nonvegetated areas;
- Evaluated by measuring deviations from planarity of single returns from hard planar surfaces;
- Measured at multiple locations within hard surfaced areas (for example, parking lots or large rooftops).

The following method is suggested, if a different one is used, it shall be documented and delivered, along with the samples locations and the results, as part of the deliverables.

Sample areas of approximately 50m^2 fitting the requirements listed above are selected across the flight line area. The sample areas are then clipped from the points of the tested flight line and classified to show the range of elevation values (maximum – minimum). The acceptable limits for that range are listed in Table 4 for the QL of the project.

Isolated noise points are expected within the sample areas and should be classified as "Withheld Point". Consideration of the effect of the expected isolated excursions over limits should be discussed with the Branch before collecting the data.

7.3.2 Interswath accuracy

Swath overlap consistency is a measure of geometric alignment of two overlapping swaths (the same principles used with swaths can be applied to overlapping lifts and overlapping projects AOI as well). Overlap consistency is the fundamental measure of the quality of the boresight adjustment of the data from each lift.

Overlap consistency shall be assessed at multiple locations within overlapping nonvegetated areas of only single returns swaths and the overlap areas tested are those between the following:

- Adjacent, overlapping parallel swaths within a project;
- Cross-tie swaths and the intersecting project swaths;
- Adjacent, overlapping lifts.

One of the methods described in the literature to determine offsets between adjacent flight lines data strips is using least squares matching, applied to LiDAR data interpolated to a regular grid.[9][5]

However, since the creation of rasters implies interpolation, a method involving less interpolation should be used by the supplier. An option solving the interpolation problem is described by Maas (2000)[11]. That method compares LiDAR points from one flight line to a TIN constructed from the LiDAR points of an adjacent flight line. An extension of that method is to use the reflectance data, in a TIN structure, to compare flight lines and measure horizontal precision in flat areas showing adequate intensity values.

The tests should include different planes, not only flat surfaces. For examples, the chosen areas with overlapping flight lines could include inclined, non-vegetated and smooth surfaces, like a road going uphill and downhill, in addition to flat surfaces.

The actual method and results shall be part of the deliverables and comply with the requirements listed in Table 4. Consideration of the effect of the expected isolated excursions over limits should be discussed with the Branch before collecting the data.

Table 4. Relative accuracy requirements

Quality Level	Smooth surface repeatability (cm)	Swath overlap difference (RMSDz) (cm)	Swath overlap maximum differences allowed (cm)
QL1	≤ 3	≤ 4	± 8
QL2	≤ 6	≤ 8	± 16
QL3	≤ 12	≤ 16	± 32
QL4	≤ 24	≤ 32	± 64
QL5	≤ 48	≤ 64	± 64

7.4 Absolute Horizontal Accuracy

Evaluating absolute horizontal accuracy for LiDAR data present greater challenges than with vector-based or digital orthophotos products. The main reason being the relative coarseness of the points collected. Structures that are readily visible and identifiable in traditional imagery are much harder to define in products created from LiDAR data.

While the comparison of overlapping areas for adjacents flight lines provides an idea of the relative horizontal accuracy (precision) of the data (Section 7.3), some potential horizontal errors will not be obvious in a comparison of flight lines in opposite direction, in the side overlap area. Furthermore, while major horizontal shifts would almost certainly show up when measuring the absolute vertical accuracy, smaller horizontal errors could be missed if vertical verification is done solely on relatively flat surfaces.

7.4.1 Absolute Horizontal Accuracy Methodology

Different methods can be used in attempting to measure absolute horizontal accuracies. Meade (2008)[13] summarise three such strategies, two of them using intensity imagery.

The first method described involves selecting features in the field for which horizontal position can be precisely measured and compared those positions with intensity images generated from the LiDAR data. For example, painted strips in parking lots could be used as such control points due to their high reflectivity and contrast to the surrounding asphalt.

The second method is to overlay the intensity image on synchronously acquired high-resolution orthophotos. The painted strips along roads going in multiple directions or strips in parking lots are examples of features that could be used to assess the absolute horizontal accuracy.

The third method to find horizontal shifts is comparing the coincidence of cross-sections measured in the field against cross-sections generated from a TIN created with the LiDAR data. Again, the field measurements should be done in areas showing significant slope, not just on flat surfaces, and in different orientations. Roadway ramps, embankment or levees could be appropriate areas for the cross-sections measurements.

Another different method that could be developed and that would provide valid horizontal absolute accuracy measurements is to plan the use of vertical ground field control boards as targets and place them to coincide with the appropriate UTM grid, in the X and Y directions. That way, by removing one of the axes uncertainties, lateral shifts in the data hitting the sides of the target could be measured.

Regardless of the strategy used, it should include different planes, not only flat surfaces, and the actual method and results shall be part of the deliverables.

7.4.2 A-Priori LiDAR horizontal accuracy estimation

$$\text{RMSEr} = \sqrt{(\theta_{laser}\ x\ AGL)^2 + \left(\sigma_{GPS_{xy}}\right)^2 + \left(\sigma_{IMUrp}\ x\ AGL\right)^2}$$

where:

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

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

$\boldsymbol{AGL}$ = Aircraft altitude above ground level at Nadir position (metres)

$\boldsymbol{\sigma_{GPS_{xy}}}$ ≅ RMSEr = Average 2D positional accuracy of the GPS system (metres) at 63% probability

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

Direct georeferencing (GPS/INS)

$$\textbf{RMSEr} = \sigma_{XY_{GPS/INS}} = \sqrt{\left(\sigma_{IMU_{rp}} x\ AGL\right)^2 + \left(\frac{1}{3}\ GSD\right)^2}$$

where:

RMSEr = Horizontal LiDAR point accuracy over flat terrain (metres) at 63% probability

$\boldsymbol{AGL}$ = Aircraft altitude above ground level at Nadir position (metres)

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

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

7.5 LiDAR Classification Accuracy and Errors

Testing of the classification accuracy shall be done on several random 1 km^2 portions of the project AOI, searching for points that have demonstrable errors in the classification value and not classified as "Withheld Point". Table 5 indicates the maximum percentage of classification errors allowed, depending on the QL level of the project.

Table 5. Classification errors per QL

Quality Level	% Errors allowed per km^2
QL1	≤ 0.5%
QL2	≤ 1.0%
QL3	≤ 2.0%
QL4 and QL5	≤ 5.0%

Points remaining in Class Code 1 (Default) that should be classified in any other required Class Code are subject to these requirements and shall be counted towards the threshold.

These requirements may be relaxed to accommodate collections in areas where the Branch agrees that classification is particularly difficult, e.g., low brush versus ground points, in which case the User Requirements Checklist would be amended as needed.

Furthermore, the following classification errors shall result in an automatic rejection of the dataset unless circumstances are identified and are accepted by the Branch:

- Flight line ridges resulting from residual data calibration or adjustment.
- Classification errors, such as artificial ground ridges between blocks, artefacts/divots (points returned from vegetation, structures or noise that are mistakenly classified as ground points) or areas where no ground points were classified due to uneven terrain.
- Duplicated points within the LiDAR datasets (2 or more points with the same XYZ coordinates).
- Aggressively thinned, interpolated, “smoothed” or artificial points unless specified otherwise in the User Requirements Checklist.

Point classification is to be consistent across the entire project. Noticeable variations in the character, texture, density or quality of the classification between tiles, swaths, lifts, or other non-natural divisions shall be cause for rejection of the entire deliverable. LiDAR data shall be adequately edge-matched.

8.0 REQUIREMENTS FOR DELIVERABLES

Although the Branch is mostly interested in the final LiDAR datasets, it is imperative to define a list of deliverables provided by the suppliers before planning the survey. Those requirements are listed in the following sections.

8.1 User Requirements Checklist for Airborne LiDAR

A kickoff meeting should be held before data acquisition to ensure that the project requirements and schedule are understood. The checklist shown below should be completed and agreed upon during the kickoff meeting.

User Requirements Checklist for Airborne LiDAR -> Project: ______________________________			
Quality Level	**Point Spacing (metres)**	**Point Density (points/m^2)**	**LiDAR Classification Classes**
☐ QL1	☐ ≤ 0.50	☐ > 8	☐ 2-Ground (bare-earth only)
☐ QL2	☐ ≤ 1	☐ > 2	☐ 2-Ground (including other surfaces)
☐ QL3	☐ ≤ 2	☐ > 0.5	☐ 3-Low Vegetation (<0.3 metre)
☐ QL4	☐ ≤ 5	☐ > 0.05	☐ 4-Medium Vegetation (0.3-1 metre)
☐ QL5	☐ ≥ 10	☐ > 0.01	☐ 5-High Vegetation (>1 metre)
Max File Size	**LiDAR file format**	**Compression**	☐ 6-Building
☐ 2 GB	☐ ASPRS .las 1.2	☐ LAS to LAZ	☐ 8-Model Key Point
☐ Other: ______	☐ Other: _______	☐ Other: __________	☐ 9-Water Body
Pulse Return	**Swath Overlap**	☐ All files	☐ 10-Railroad
☐ First	☐ 30% (urban)	☐ Back-up only	☐ 11-Paved Road
☐ Last	☐ 50% (forested)	**Intensity Imagery**	☐ 13-Unpaved Road
☐ All	☐ Other: _______	☐ Pixel Size _________	☐ 14-Parking
Horizontal Datum	**Coordinate System**	**Optional Imagery**	☐ 15-Driveway
☐ NAD 83	☐ UTM (Zone____)	**Synchronous**	☐ 16-Bridge Deck
Vertical Datum	☐ bcalber	☐ High-Res. RGB	☐ 17-All Miscellaneous
☐ CGVD2013	☐ Other: _______	☐ Multispectral	☐ 18-Miscellaneous Permanent
Geoid	**Product Units**	☐ None	☐ 19-Miscellaneous Temporary
☐ CGG2013	☐ Metres	**Separate**	☐ Other: ______________________
☐ Other: ______	☐ Other: _______	☐ Stereo Imagery	☐ Other: ______________________
Reports and Procedures to submit			**Classification Errors (per km2)**
☐ Mission Planning		☐ QA Procedures and Reports	☐ ≤ 0.5%
☐ Operation Parameters		☐ Production & Processing Report	☐ ≤ 1.0%
☐ Ground Control & Base Station		☐ QC Procedures and Reports	☐ ≤ 2.0%
☐ Survey Report & Flight logs		☐ Metadata	☐ ≤ 5.0%
☐ Calibration & Adjustment		☐ Final Project Report	☐ Other: ___________

8.2 Mission Planning Report

The following indicates the minimum content of the mission planning report. Mission planning also includes the assessment of military and other controlled airspace where special permits may be required.

- Project important dates:
  - Start of collection (leaf-on/off)
  - Deliverables milestones
  - Project final deadline
- Aircraft information
- Airport information
- Planned survey area and buffer
- Tidal considerations (if any)
- Calibration plans
- Planned Flight lines
- Planned Flight line overlap
- Planned above ground flying height
- Planned GPS stations and control points
- Planned fieldwork procedure
- Planned procedure for re-flights
- Planning to account for weather, land cover and terrain
- Point density estimations (average and minimum)
- Point spacing estimations (lateral, forward and combined)

8.3 Operational Parameters Report

LiDAR sensors each have variable requirements for flying height to meet project specifications. So it is not necessary to specify standard flying heights. Flight and mission planning is typically the responsibility of the acquisition supplier and will vary greatly depending on the sensor used for the acquisition.

Even though operational parameters will be different for each sensor, focus shall be put on ensuring that the results meet the project specifications. Table 6 list relevant operational parameters for LiDAR data collection. The values for each of those parameters, when applicable, shall be included in the Operational Parameters Report.

Table 6. Operational Parameters for LiDAR

Operational Parameters for LiDAR Collection	
System (Name and S/N)	Total Swath Width (FOV) (m)
Scanning Pattern	Beam Divergence (mrad)
Pulse Length (ns)	Footprint Diameter (m)
Laser Wavelength (nm)	Nominal Flying Altitude AMSL (m)
Laser Pulse Energy (µJ)	Average Airspeed (kts)
Laser Range (m)	Range/Intensity Mode
Number of Returns (per beam/pulse)	System Controller Firmware
Pulse Repetition Frequency Effective (kHz)	Laser Power Class (W)
Pulse Repetition Frequency Output (kHz)	Receiver Aperture Stop (°)
Scan Rate (kHz)	Number of Flight Lines
Scan Angle Encoder (°)	Maximum Flight Line Length (km)
Scan Field of View (FOV) full angle (°)	Swath Overlap (%)

8.4 Ground Control and Base Station Reports

Surveys should be conducted to establish ground truth data at representative sites throughout the project area.

Ground Control and Base Station Reports shall include:

- Control points reports
- Altitude plot
- GPS distance from base station
- GPS base station info
  - Base station name
  - Latitude/Longitude (DD-MM-SS.SSS)
  - Base height (ellipsoidal meters)
  - Maximum Position Dilution of Precision PDOP
- GPS processing summary
  - Horizontal GPS standard deviation of estimated vector values
  - Vertical GPS standard deviation of estimated values
  - Notes on GPS quality
  - A-posteriorly networking results
- GPS quality
  - PDOP plot
  - GPS Horizontal and Vertical Accuracy

8.5 Calibration and Adjustment Report

Post-flight reports outlining the calibration methodology, comparing collected LiDAR (before any post-processing or re-calibration) shall be submitted. If any modifications are made to the calibration parameters, including sensors, suppliers shall provide a post, re-calibration control report along with the pre-calibration control report.

Calibration and Adjustment Reports shall include:

- System calibration plans and reports
- Adjustment and fitting procedures
- Angular bore-sighting and lever-arm offsets
- Laser offset
- Laser scanner scale and offset parameters
- Least squares adjustment report (if applicable)
  - Variance-covariance matrix of calibration parameters
  - Flight line ID and best estimated trajectory
  - Adjustment parameters

8.6 Survey Reports and Flight Logs

Following mobilisation, the supplier shall submit daily acquisition and field condition reports that provide a summary of the conditions during the time of the survey, for each lift. The content of these reports is listed below.

- Project name
- Date of collection
- Pilot/Operator names
- Aircraft registration and type
- Number of flight lines (FL)
- FL collected and trajectories
- For each FL:
  - Scan direction
  - Start/stop
  - Altitude
  - Scan angle (if applicable)
  - Ground speed
- Weather conditions
- Tidal considerations (if any)
- Ground conditions
- Vegetation conditions

- Extent of collection
- Automatic gain control switch setting

8.7 Quality Assurance Procedures and Reports

The reports detailing the QA done by the supplier shall contain, as a minimum:

- Quality Assurance procedure
- Relative accuracies/Precision (inter and intraswath)
- Preliminary absolute vertical accuracy assessment
- Cross Track Spacing
- Along Track Spacing
- Point Spacing Lateral
- Point Spacing Forward
- Point Spacing Combined
- Point Density Average
- Point Density Minimum

8.8 Production and Processing Report

A summary of the data production and processing shall be submitted with the processed LiDAR datasets and include:

- Processing procedures
- Data range for data capture
- Date of project beginning and completion
- Representation of spatial extent of deliverables
- Project tiling footprint
- Any planimetric files used to assist the data classification (e.g., buildings footprints, water bodies outlines, roads surface) in shapefile format.
- Each LAS file shall contain the following information:
    - Horizontal Datum
    - Vertical Datum
    - Projection
    - Horizontal and Vertical Units

- Each record shall include the following fields (at a minimum):
  - X, Y, Z coordinates
  - Flight line data
  - Intensity value
  - Return number
  - Number of returns
  - Scan direction
  - Edge of flight line
  - Scan angle
  - Classification
  - GPS timestamp

8.9 Quality Control Procedures and Reports

The reports detailing the QC done by the supplier shall contain, as a minimum:

- Description of the QC process
- Results of QC:
  - Data Coverage/Voids
  - Relative accuracy/Precision
  - Absolute vertical accuracy
  - Ground Point density
  - Ground Point spacing
  - Classification accuracy estimation

A Final LiDAR Project Report shall be delivered once processing is completed along with the final delivered products. The project report serves as the master report for the entire project and includes a detailed explanation of the processing and qualitative assessment performed on the data, as well as the project metadata.

9.0 METADATA FORMAT AND CONTENT

Metadata can be viewed as data about the content, quality, condition, and other characteristics of data. The purpose of the standard is to make available a common set of terminology and definitions for the documentation of digital geospatial data. The standard that shall be used by the data suppliers to document the project metadata is the "Content Standard for Digital Geospatial Metadata" (2008)[7] from the Federal Geographic Data Committee.

The information included in the FGDC standard is based on the four roles of metadata:

- Availability - information required by a user to determine the availability of a set of geospatial data.
- Fitness for use - information needed by a user to determine if a set of data meets a specific intended use.
- Access - information needed to identify means of accessing the set of geospatial data.
- Transfer – information needed to process and use a set of geospatial data.

The major sections that shall be documented in the metadata are:

- Identification Information
- Data Quality Information
- Spatial Data Organization Information
- Spatial Reference Information
- Entity and Attribute Information
- Distribution Information
- Metadata Reference Information

All metadata files shall contain sufficient content to detail the full product lineage, including flight dates and times, datum information, re-projections, re-sampling algorithms, processing steps, field records, all procedures used for data processing, QA, QC, and any other pertinent information. Metadata shall be delivered in eXtensible Markup Language (XML) format. The detailed instructions for filling out the metadata can be found in the FGDC (1998) standard.

10.0 REFERENCES

[1] American Society for Photogrammetry & Remote Sensing, "LAS Specification Version 1.2.", 2008. Web: http://www.asprs.org/wp-content/uploads/2010/12/asprs_las_format_v12.pdf

[2] American Society for Photogrammetry & Remote Sensing, "LAS Specification Version 1.4-R13.", 2013. Web: http://www.asprs.org/wp-content/uploads/2010/12/LAS_1_4_r13.pdf

[3] American Society for Photogrammetry & Remote Sensing, "ASPRS LiDAR Guidelines: Horizontal Accuracy Reporting.", 2005. Web:http://www.asprs.org/a/society/committees/standards/Horizontal_Accuracy_Reporting_for_Lidar_Data.pdf

[4] American Society for Photogrammetry & Remote Sensing "ASPRS Positional Accuracy Standards for Digital Geospatial Data", Edition 1, Version 1.0. November 2014 / Photogrammetric Engineering & Remote Sensing Vol.81, No.3, March 2015. Web: http://www.asprs.org/a/society/committees/standards/Positional_Accuracy_Standards.pdf

[5] Behan, A., 2000. "On the Matching Accuracy of Rasterised Scanning Laser Altimeter Data." IAPRS, Vol. 33, Part 2. Web: https://dit.ie/media/built/images/spatialplanning/MatchingAccuracy.pdf

[6] Federal Geographic Data Committee. FGDC-STD-001-1998. "Content standard for digital geospatial metadata.", 1998. Web: https://www.fgdc.gov/standards/projects/metadata/base-metadata/v2_0698.pdf

[7] Federal Geographic Data Committee. FGDC-STD-012-2002. "Content standard for digital geospatial metadata: Extensions for Remote Sensing Metadata.", 2002. Web: https://www.fgdc.gov/standards/projects/csdgm_rs_ex/MetadataRemoteSensingExtens.pdf

[8] Gatziolis, D., Andersen, H.E., 2008. "A guide to LIDAR data acquisition and processing for the forests of the Pacific Northwest." Gen. Tech. Rep., Portland, OR, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. Web: http://www.fs.fed.us/pnw/pubs/pnw_gtr768.pdf

[9] Heidemann, H. 2014. "LiDAR Base Specification" - ver. 1.2, November 2014. U.S. Geological Survey Techniques and Methods, book 11, chap. B4. Web: https://pubs.usgs.gov/tm/11b4/pdf/tm11-B4.pdf

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

[11] Maas, H.-G., 2000. "Least-squares matching with airborne laserscanning data in a TIN structure.", International Archives of Photogrammetry and Remote Sensing, 33(Part 3A):548–555. Web: http://www.isprs.org/proceedings/XXXIII/congress/part3/548_XXXIII-part3.pdf

[12] Maas, H.G., 2002. "Methods for Measuring Height and Planimetry discrepancies in Airborne Laserscanner Data.", Photogrammetric Engineering & Remote Sensing, Vol. 68, No. 9. Web: https://tu-dresden.de/bu/umwelt/geo/ipf/photogrammetrie/ressourcen/dateien/forschung/publikationen/pubdocs/2002/2002_Maas_PERS2002.pdf?lang=en

[13] Meade, M.E., From the Ground Up: Horizontal Accuracy Assessment in LiDAR., POB, posted on November 1, 2008. Web: http://www.pobonline.com/articles/92408-from-the-ground-up-horizontal-accuracy-assessment-in-lidar

[14] Province of British Columbia (GeoBC): "Specifications and Guidelines for Control Surveys Using GPS Technology", 2010. Web: http://www.geobc.gov.bc.ca/base-mapping/atlas/gsr/documents/ControlSurveysGPS_2010.pdf

APPENDIX A: ACCURACY REPORTING

Table 7 shall be used by the data supplier to report the horizontal and vertical accuracies of the LiDAR data. (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 checkpoint 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:
Δ_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:
Δ_i is the i^{th} residual error in the specified direction
$\bar{\Delta}$ is the mean error is the specified direction
i is an integer ranging from 1 to n and
n the number of checkpoints

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

where:
N_i is the i^{th} measured coordinate being evaluated, in the specified direction
N_i' is the corresponding checkpoint 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 RMSEr = $\sqrt{(RMSE_x^2 + RMSE_y^2)}$ (1dRMSEr, at 63% probability)

where:
RMSEx is the RMSE in the x direction, and
RMSEy is the RMSE in the y direction

Table 7. Accuracy Report for LiDAR data

Point ID	Measured Values [metres]			Survey Checkpoint Values [metres]			Residuals (errors) [metres]		
	Easting (x)	Northing (y)	Elevation (z)	Easting (x)	Northing (y)	Elevation (z)	Δx Easting	Δy Northing	Δz Elevation
GCP1							0.000	0.000	0.000
GCP2							0.000	0.000	0.000
GCP3							0.000	0.000	0.000
GCP4							0.000	0.000	0.000
GCP5							0.000	0.000	0.000
GCP6							0.000	0.000	0.000
GCP7							0.000	0.000	0.000
GCP8							0.000	0.000	0.000
GCP9							0.000	0.000	0.000
GCP10							0.000	0.000	0.000
GCP11							0.000	0.000	0.000
GCP12							0.000	0.000	0.000
GCP13							0.000	0.000	0.000
GCP14							0.000	0.000	0.000
GCP15							0.000	0.000	0.000
GCP16							0.000	0.000	0.000
GCP17							0.000	0.000	0.000
GCP18							0.000	0.000	0.000
GCP19							0.000	0.000	0.000
GCP20							0.000	0.000	0.000
Number of checkpoints							20	20	20
Mean Error							0.000	0.000	0.000
Standard Deviation							0.000	0.000	0.000
Root Mean Square Error RMSE, 1dRMSE at 68% Confidence Level							0.000	0.000	0.000
Radial Horizontal Accuracy RMSEr, 1dRMSEr at 63% Confidence Level							0.000		

APPENDIX B: FILES NAMING CONVENTIONS

For LiDAR 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_092l081_1_1_3_xyes_31_utm_150105.las

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)
AGL	Aircraft altitude above ground level at Nadir position
AMSL	Above Mean Sea Level
AOI	Area of Interest
ASL	Airborne LiDAR Scanning
ASPRS	American Society for Photogrammetry and Remote Sensing
CL	Confidence Level
FGDC	Federal Geographic Data Committee
FL	Flight Line
FOV	Field of View
GPS	Global Positioning System
IMU	Inertial Measurement Unit
LiDAR	Light Detection and Ranging
MLS	Mobile LiDAR Survey
NIR	Near Infra-Red
NPD	Nominal Point Density
NPS	Nominal Point Spacing
PDOP	Position Dilution of Precision
QA	Quality Assurance
QC	Quality Control
QL	Quality Level
RGB	Red-Green-Blue
RMSEr	Horizontal (radial) Root Mean Square Error
$RMSE_x$	Horizontal (x) Root Mean Squared Error
$RMSE_y$	Horizontal (y) Root Mean Squared Error
$RMSE_z$	Vertical (z) Root Mean Squared Error
TIN	Triangular Irregular Network
UAV	Unmanned Aerial Vehicle
ULS	Unmanned LiDAR Survey
USGS	United States Geological Survey
XML	Extensible Markup Language

GLOSSARY OF TERMS

Source: modified from Heidemann (2014)[9] and ISO/TC 211 (2015)[10]

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.

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.

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

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

Checkpoint - A surveyed point used to estimate the positional accuracy of a geospatial dataset against an independent source of greater accuracy. Checkpoints are independent of, 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 is 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 on true ground position that is equal to or smaller than the reported accuracy value.

Control point (calibration point) - A surveyed point used to adjust a dataset geometrically to establish its positional accuracy relative to the real world. Control points are independent of, 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, an x/y coordinate with an associated z-value.

Correction - Compensation for an estimated systematic effect.

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.

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.

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, analyse, 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 the 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 location through trilateration (determining position with respect to two other points by measuring the distance between all three points).

Horizontal accuracy - Positional accuracy of a dataset with respect to a horizontal datum.

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, the 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.
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.

Light Detection And Ranging (LiDAR) - An instrument that measures the 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.

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/Quality Control (QA/QC)), and other supporting data (e.g., survey points, shapefiles).

Model - Abstraction of some aspects of reality.

Nominal Point Density (NPD) - A common measure of the density of a LiDAR dataset; NPD is the typical or average number of points occurring in a specified areal unit. The NPD is typically expressed as points per square metre (pts/m^2). This value can be 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:

$$NPD = 1/NPS^2$$

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

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

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.

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 centred on the vehicle's centre 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 fulfils requirements. Accuracy (exactitude) and precision (repeatability) are the means used to evaluate the quality of the source data and DEM products.

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

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

Raster - Set of regularly spaced, continuous cells with, in the case here, bare-earth elevation values attached to the centre 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 centred on the vehicle’s centre 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 RMESy) 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 here:

$RMSE_x$ The horizontal root mean square error in the x direction (easting):

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

where:
X_i is the set of n x coordinates being evaluated,
X_i' is the corresponding set of checkpoint *x* coordinates for the points being evaluated,
n is the number of x coordinate checkpoints, and
i is the identification number of each checkpoint from 1 through n.

$RMSE_y$ The horizontal root mean square error in the y direction (northing):

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

where:
Y_i is the set of n y coordinates being evaluated,
Y_i' is the corresponding set of checkpoint y coordinates for the points being evaluated,
n is the number of y coordinate checkpoints, and
i is the identification number of each checkpoint from 1 through n.

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

$$\sqrt{(RMSE_X^2 + RMSE_Y^2)}$$

where:
$RMSE_x$ is the RMSE in the x direction, and
$RMSE_y$ is the RMSE in the y direction.

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

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

where:
Z_i is the set of n z values (elevations) being evaluated,
Z_i' is the corresponding set of checkpoint elevations for the points being evaluated,
n is the number of z checkpoints, and
i is the identification number of each checkpoint from 1 through n.

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.

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. Vertical accuracy is an indicator of quality for geospatial 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.

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 centred on the vehicle's centre 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 TABLES