Specifications for Airborne LiDAR for the Province of British Columbia

Version 5.3
Issue date: 2023-05-03
Victoria, BC

GeoBC

British Columbia | Ministry of Water, Land and Resource Stewardship

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Record of Amendments

Version	Revised by	Revision Description	Approved by	Date
1.0	Harald Steiner	Re-write	Harald Steiner, PEng	31-Mar-2013
2.0	D. Garnham	Major revision of 1.0	Harald Steiner, PEng	21-Mar-2014
3.0	Isabelle Paquin Brett Edwards James Thompson Robert Prins	Revision to align with GeoBC 2016 DEM specifications	Harald Steiner, PEng	04-Oct-2016
3.1	Brett Edwards James Thompson	Revisions to classes, data formatting, reporting, naming and other minor edits	Robert Prins	30-Apr-2018
4.0	Yuna Jiao Brett Edwards Jordan Godau	Re-write	Harald Steiner, PEng	30-Apr-2019
5.0	Samantha Grant Brett Edwards Jordan Godau James Thompson	Re-write	Harald Steiner, PEng	09-Apr-2020
5.1	Samantha Grant Kaitlyn McLaren James Thompson	Revisions to acquisition, ground control, reporting, classification accuracy/errors, naming, formatting, and other minor errors	Harald Steiner, PEng	30-Apr-2021
5.2	Brett Edwards Spencer Floyd Samantha Grant Natalie Jackson Kaitlyn McLaren James Thompson	Revisions to ground control and geodetic reference frame (GNSS survey) requirements, other minor updates.	Harald Steiner, PEng	4-May-2022
5.3	Brett Edwards Spencer Floyd	Minimum classification requirements added. Final coverage delivery format changed to Geopackage. GUID requirements removed. Custom VLR record added. Isolated noise thresholds added.	Harald Steiner, PEng	3-May-2023

1.0 Introduction

These specifications provide geospatial data vendors with standards and requirements to produce LiDAR datasets collected by airborne LiDAR scanning systems (ALS). The objective of these specifications is to ensure consistent, high-quality LiDAR product deliverables for the Province of British Columbia.

These LiDAR specifications supersede all previous LiDAR specifications. This document will be updated and maintained through advances in LiDAR technology and ongoing feedback from industry.

The term “Branch”, used herein, shall mean GeoBC of the Ministry Land, Water and Resource Stewardship 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 specifications detailed in this document.

To this documentation, the word “shall” indicates a mandatory specification and “should” indicates a preferred specification.

2.0 Purpose and Scope

This document outlines specifications for quality assurance (QA) and quality control (QC) of LiDAR data. The Branch refers to LiDAR data in this document as discrete return LiDAR data; this document does not address full waveform LiDAR data and deliverables.

The purpose of these specifications is to ensure high levels of data integrity, including:

- Achievement of standards regarding data accuracy and quality;
- Consistent deliverables;
- Product completeness.

3.0 Acquisition and Quality Assurance

Quality assurance (QA) is a set of procedures in project planning that ensure the quality of data and through systematic collection and processing methods. These measures ensure the quality of source data, before and during the acquisition stage of a project.

3.1 LiDAR Acquisition Guidelines

Flight and mission planning are typically the responsibility of the vendor, as LiDAR sensors have variable requirements and operational parameters. The vendor shall ensure operational standards and project specifications are met.

Errors due to LiDAR system malfunctions shall be recorded and reported to the Branch through flight reporting (see Section 6.7). A malfunction is defined as a failure anywhere in the acquisition platform that causes an interruption to the normal operation of the system. Any sensor changes, failures, or replacements prior to or during the data collection shall also be reported.

3.1.1 Flight and Mission Planning

The proposed flight plan covering the geographic area of interest (AOI) and buffered project area (BPA) (see Section 3.6) shall be defined as a set of flight lines attributed with planned flying height above ground level (AGL) and associated swath side lap.

A flight line should be centred on a border of the AOI before positioning additional flight lines.

Side lap shall be at minimum 30% on each side of swaths within the BPA, unless otherwise specified in the project contract.

Cross ties are flight lines that are perpendicular to the main acquisition flight plan. They can provide accuracy validation in support of LiDAR adjustments where areas of poor position dilution of precision (PDOP) may occur [1]. Cross ties should be included in mission planning.

3.1.2 Flight Parameters

Flying height is defined as the aircraft altitude above ground level (AGL) at nadir position. Maintaining a constant flying height above ground, while adhering to flying height safety protocols, reduces systematic errors that are difficult to detect, such as laser range scale errors. A constant flying height also ensures a consistent laser beam footprint size, which can affect the horizontal accuracy of the data. 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.

Flying height shall be planned and executed for the project to ensure the laser pulse footprint at nadir does not exceed the ≤ 0.35 m laser pulse footprint diameter (see Section 3.7) by more than 10% (≤ 0.39 m). Flying height can be planned according to the following equation:

$$H = \frac{d}{\gamma}$$

where:

H is the planned flying height AGL (metres)

d is the laser pulse footprint diameter (i.e., ≤ 0.35 m) (metres)

γ is the beam divergence (radians)

Acquisition trajectories shall be provided to the Branch and assessed for this requirement. See Section 6.10 for trajectory deliverable requirements.

The aircraft bank angle shall not exceed 20° unless the safety of the aircrew or aircraft is at risk.

3.1.3 Environmental Conditions

Environmental conditions for LiDAR data collection shall follow these guidelines:

- Atmospheric conditions shall be cloud and fog free between the aircraft and ground during all collection operations.
- Monitor solar activities during acquisition phase (Space Weather Forecast shall be determined using the Natural Resources Canada (NRCan) Canadian Space Weather Forecast Centre: http://www.spaceweather.gc.ca/index-en.php).

- Ground conditions shall be snow free. Very light, non-drifted snow may be acceptable with prior approval from the Branch.
- Ground conditions shall be free of extensive flooding or other form of inundation, without prior approval from the Branch.
- Areas affected by tides should be planned for collection around low tide. Low tide is defined as the farthest ebb of a tidal water body for a given place and time.
- Scanning should occur within operational limits of the system, including temperature and altitude ranges.

3.1.4 Mission Planning Deliverables

Flight plans shall be provided as shapefiles. System specifications and operational parameters shall be documented and submitted to the Branch. See Section 6.6 for Mission Planning Report requirements.

3.2 System Calibration

Calibration of a LiDAR acquisition system refers to the process of identifying and correcting systematic errors in the sensor configuration (misalignments and offsets), hardware, software, and procedures. LiDAR system calibration and maintenance shall be performed to ensure proper function of the LiDAR system.

Normal aircraft operations can induce slight variations in sensor component mounting. Therefore, a LiDAR system calibration shall be performed before acquisition begins, as well as at the end of the project. If any modifications are made to any of the calibration parameters (including sensors), the vendor shall provide a new LiDAR system calibration report after any modifications.

The ideal calibration site is clear of vegetation and has both flat and sloped planar surfaces of various aspects. Airports are ideal calibration sites, as they contain a significant amount of flat terrain, as well as sloped rooftops. LiDAR system calibration flights shall be conducted at the same AGL flying height as the planned collection mission to meet the laser pulse footprint specification in Section 3.7.

A report containing all calibration parameters and results shall be submitted to the Branch prior to acquisition (see Section 6.4.2). Vendors shall utilize the Branch's proprietary program LiCal© on the calibration LiDAR swaths and deliver all LiCal© outputs (see Section 6.4.1). The LiDAR point data from this calibration shall be submitted to the Branch prior to acquisition (see Section 6.1).

Calibration shall be processed and delivered in the same horizontal/vertical datums and coordinate reference system as the project (see Section 4.1.3). An instrument calibration performed by the manufacturer shall be provided to the Branch upon request.

3.3 Error Budget

Errors can be categorized as either random or systematic. Systematic errors, with respect to LiDAR, are errors that can be compensated for through a LiDAR system calibration (see Section 3.2). Random errors include those errors that remain once systematic errors are removed.

Most systematic errors in LiDAR data are caused by angular misalignments and lever-arm offsets relating the various components of the scanning system. Other sources of systematic errors include scan angle errors and range scale errors. Regardless of the source of error, any indication of systematic errors in the data before, during, or after data processing shall be reported to the Branch as soon as the error is identified. All systematic errors shall be accounted for and corrected upon data submission.

Random errors will always remain in the point cloud after systematic errors have been corrected. Remaining random errors should be small in magnitude and randomly distributed throughout the data. Section 5.0 and subsections specify limits for random errors.

3.4 Data Adjustments

The Branch defines data adjustment as correcting LiDAR point cloud data for unmodelled errors that remain after performing a LiDAR system calibration. These additional errors should be corrected via data adjustment methods (e.g., strip adjustment, Helmert transformation, etc.). The vendor shall supply a detailed adjustment report describing the methodology, software used, and all output results.

3.5 Geodetic Frame and Ground Control

Reference points and ground control points (GCPs) shall be measured with a Global Navigation Satellite System (GNSS) survey during project acquisition. This section describes the requirements for obtaining adequate ground control for LiDAR adjustment and quality control, and for situating that control in the appropriate geodetic reference frame.

3.5.1 Types of GNSS Survey Points

These specifications use the following terms to identify different types of reference and control points, to be collected by GNSS survey, as defined by the Branch:

- **active or passive geodetic reference station** – Canadian Active Control System (CACS) station, British Columbia Active Control System (BCACS) station, or a GNSS point occupied on a passive Canadian Base Network (CBN) station.
- **passive vertical control** – GNSS occupied on an existing Management of Survey Control Operations and Tasks (MASCOT) Geodetic Control Marker (GCM) with vertical integration. More information on selection of acceptable MASCOT GCMs and related data processing is outlined in Section 3.5.2. [2]
- **ground control point (GCP)** – Newly established, on-site survey point collected with GNSS, used for geometric adjustment or quality control of the LiDAR point cloud. GCPs may be described with markers, paint lines, targets, or be unmarked. GCPs shall be classified as either:
    - **non-vegetated vertical accuracy (NVA) GCP** – Point located in open or urban terrain, including bare soil, short grass, asphalt, or concrete surfaces.
    - **vegetated vertical accuracy (VVA) GCP** – Point located in any vegetated land cover types, including tall weeds and crops, cut blocks, and fully forested areas.
        - VVA GCPs shall only be included if specified in the project contract.

3.5.2 Collection and Processing

All aerial LiDAR survey missions shall be referenced to GNSS-observed control points. Ground control surveys that fulfill minimum Branch requirements shall adhere to the following guidelines:

- Measurements of control points shall be performed during project acquisition using a GNSS survey.
- Vertical accuracy of GCPs shall be five times better than the required vertical accuracy of LiDAR (see Section 5.1) and adhere to the values in Table 1. Vertical accuracy of coordinates measured on passive vertical control (MASCOT GCMs) shall meet QL2. To meet vertical accuracy requirements, please refer to the “Specifications and Guidelines for Control Surveys Using GPS Technology” [3].

Table 1: Vertical Accuracy Requirements of GNSS Points per Quality Level

Quality Level (QL)	LiDAR Vertical Accuracy $RMSE_z$, 68% confidence level	GNSS Point Vertical Accuracy $RMSE_z$, 68% confidence level
QL1	≤ 5.0 cm	≤ 1.0 cm
QL2	≤ 10 cm	≤ 2.0 cm
QL3	≤ 20 cm	≤ 4.0 cm
QL4	≤ 1.0 m	≤ 20 cm
QL5	≤ 3.0 m	≤ 60 cm

- At least one passive vertical control point shall be occupied on a MASCOT GCM, unless otherwise specified in the project contract.
    - New coordinates of points occupied on MASCOT GCMs shall be independently produced using NRCan’s Precise Point Positioning (PPP) service (https://webapp.geod.nrcan.gc.ca/geod/tools-outils/ppp.php). Published coordinates of the MASCOT GCM are not to be used.
    - If no MASCOT GCM exists within the project AOI, the nearest MASCOT GCM that meets the criteria below shall be occupied.
    - If the selected MASCOT GCM is located within the project AOI and meets the other criteria for GCPs as described in Section 3.5.1, the point occupied on the MASCOT GCM may be used as a GCP. If the point used as a GCP, it shall be classified as NVA or VVA.
    - The vertical integration status of the marker at time of occupation shall be “INTEGRATED”.
    - The method of vertical integration for the marker shall be, in order of preference, “Spirit Level”, “GPS SAT. POS.”, or “NON-SIMUL TRIG”.
    - Vertical accuracy of coordinates measured on MASCOT GCMs shall meet QL2, as defined in Table 1.

- More information on the MASCOT network, and access to the MASCOT database is available at https://www2.gov.bc.ca/gov/content/data/geographic-data-services/geo-spatial-referencing/survey-control-operations [2].

- GCP surveys shall be processed using either differential GNSS, or single point positioning.
    - If the survey uses differential GNSS processing, all GCPs shall be referenced to at least one active or passive geodetic reference station, using either: a Canadian Base Network (CBN) station, a Canadian Active Control System (CACS) station, or a British Columbia Active Control System (BCACS) station.
    - If the survey uses single point positioning, the point shall be post-processed using NRCan's PPP service (https://webapp.geod.nrcan.gc.ca/geod/tools-outils/ppp.php).
- Coordinates for points on mainland BC shall be processed using NAD83 (CSRS) epoch 2002.0. Coordinates for points on Vancouver Island shall be processed using NAD83 (CSRS) epoch 1997.0. These epochs have been adopted by the Branch, as outlined by NRCan (https://www.nrcan.gc.ca/maps-tools-publications/maps/adopted-nad83csrs-epochs/17908).
- The vertical datum shall be CGVD2013 for all submitted control. Refer to the latest published geoid model from the Geodetic Survey of Canada (https://webapp.geod.nrcan.gc.ca/geod/data-donnees/geoid.php).
- The horizontal accuracy of the GCPs shall be ten times better than the theoretical horizontal accuracy of LiDAR ($RMSE_r$) at 63% confidence over flat terrain as outlined in Section 5.5.3. To meet horizontal accuracy requirements, please refer to the "Specifications and Guidelines for Control Surveys Using GPS Technology" [3].
- GNSS observations shall be conducted by a designated professional (geomatics technologist, professional land surveyor, geomatics engineer). Ground control reports (see Section 6.12) shall be signed by a designated professional.
- Digital images of marked GCPs with point identification information shall be provided in the ground control report (see Section 6.12).

As a guideline, the following should be taken into consideration in the planning and execution of GNSS surveys:

- Sky obstructions. Take observations in clear, open areas free from vegetation and overhead obstructions (e.g., trees, buildings, etc.)
- Avoid highly reflective surfaces (e.g., tin roofs or vehicles), and areas with heavy vehicle traffic to mitigate multipath error.
- Geomagnetic conditions on the day of observations.
- Geometry and number of satellites overhead during the time of observation.
- Appropriate baseline lengths for differential processing.
- All project extremities should have GCPs.

3.5.3 Quantity and Distribution of Control Points

The number of GCPs required for the project will depend largely on the size and location of the project site(s). It is the responsibility of the vendor to determine the final number of GCPs needed for each individual project area, however, the number of GCPs for assessing accuracy of the point cloud shall adhere at a minimum to the following requirements:

- GCPs used to assess the quality of the point cloud shall be located within the AOI.
- GCPs shall be evenly distributed within each isolated project area[1].
- GCPs shall be non-vegetated points located in open or urban terrain including bare soil, short grass, asphalt, and concrete surfaces.
- GCPs shall not be located on objects that would not be classified as ground in the acquired point cloud.
- If a least-squares LiDAR strip adjustment is performed, 10 GCPs are required per isolated project area.
- If a least-squares LiDAR strip adjustment is not performed, 20 GCPs are required per isolated project area.

3.5.4 Deliverables

All GNSS points shall have a corresponding shapefile delivered with the attribute fields found in Section 6.13, following the naming conventions provided by the Branch.

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

Vendors shall supply a full control report outlining at minimum the requirements listed in Section 6.12, including any reports related to GNSS processing (e.g., post-processing, least-squares adjustment, etc.).

Vendors should refer to "Specifications and Guidelines for Control Surveys Using GPS Technology" [3] for survey best practices.

3.6 Spatial Distribution of Pulses and Planned Area Coverage

The project AOI shall be externally buffered by 100 metres to create the buffered project area (BPA). LiDAR data shall be collected to the full extent of the BPA, and all products shall be generated to the full extent of the BPA.

All collected swaths 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 LAZ files, except data that falls outside the BPA.

3.6.1 Spatial Regularity

The spatial distribution of pulses shall be collected uniformly to represent a regular lattice distribution [1]. Although LiDAR instruments do not produce regularly distributed points, collections shall be planned and executed to generate net nominal pulse spacing (NPS) (see Section 5.3.3) that approximates a regular lattice of points.

The regularity of the point pattern throughout the dataset should be assessed using a method comparable to the following steps using single return points [4]:

- Generate a density grid with cell sizes equal to twice the required NPS for the Quality Level (QL) of the project (see Section 5.1).
- Ensure that 90% of the cells in the grid contain at least one usable LiDAR point that falls within the usable centre part (typically 95%) of each individual swath.
- Exclude acceptable data voids (see Section 3.6.3).

3.6.2 Side Lap and Coverage Check

A daily coverage check shall be performed in the field by loading the cumulatively acquired LiDAR dataset, including data within the BPA, into a capable software package. The data shall be examined for the following:

- Incomplete coverage of the AOI and BPA (see Section 3.6)
- Insufficient side lap/overlap between swaths (see Section 3.6.2)
- Data voids (see Section 3.6.3)
- Any other anomalies caused by sensor or acquisition errors

These checks shall be repeated prior to the aircraft leaving the survey area to ensure full coverage to the extent of the AOI and BPA. Re-flights shall be planned and completed if data voids exist, or errors are found. The Branch shall not be held financially responsible for the cost of remobilizing aircraft for re-acquisition.

3.6.3 Data Voids

Data voids can occur in LiDAR data collection due to various reasons, including surface absorbance, scattering, or refraction of LiDAR pulses. Data voids covering areas larger than $(4 \times NPS)^2$ for single swaths are not acceptable, except when caused by the following [4]:

- Waterbodies;
- Areas of little near infrared (NIR) reflectivity (i.e., dark tar asphalted surfaces);
- Where appropriately filled in by another swath [4].

Object shadowing (e.g., buildings, towers, vertical cliffs) shall be accounted for through subsequent flight lines, unless otherwise stipulated in the project contract.

3.7 Beam Divergence and Laser Pulse Footprint

The Branch defines beam divergence of a LiDAR system as an angular measure, in milliradians (mrad), of the spread of an emitted signal pulse. The emitted signal pulse assumes a 2D Gaussian distribution [5], where the pulse beam diameter shall be reported at $1/e^2$ width[2].

Unless otherwise specified, LiDAR acquisition shall be planned with a $\leq$ 0.35 m laser pulse footprint diameter at $1/e^2$ width.

[2] The $1/e^2$ width of a 2D Gaussian beam is the width where the intensity is $1/e^2$ or about 13.5% of its central peak value [5].

4.0 Data Processing and Management

This section describes final LiDAR deliverables, including specific data format properties, classification, tiling, and data delivery.

4.1 Data Format

All LiDAR data shall be delivered in LAZ 1.4 format, with Point Data Record Format (PDRF) 6 [6] unless otherwise specified in the project contract. Specific data format properties are discussed here for clarification and emphasis. However, data formatting shall be fully compliant with the ASPRS LAS Specifications v1.4 [6] unless otherwise specified in this document or the project contract.

4.1.1 Intensity

The intensity value for a point is the numerical representation of the return magnitude and shall always be included for each discrete return. Intensity values shall always be reported as a 16-bit, unsigned value. If the dynamic range of the sensor used is not 16 bits, it shall be normalized to a 16-bit value according to the relationship:

$$Intensity_{16-bit} = Intensity_{raw} \times \frac{63{,}536}{intensity\ dynamic\ range\ of\ sensor}$$

See the ASPRS LAS Specification v1.4 for additional information regarding intensity values [6].

4.1.2 GPS Time

GPS time data in delivered LAS/LAZ files shall be recorded as Adjusted Standard GPS time. All points within a dataset deliverable shall have a valid GPS time for each point record. GPS week and GPS time errors will not be accepted by the Branch and is criteria for rejection of the delivered dataset.

4.1.3 Coordinate Reference System

In all projects and files, the coordinate reference system (CRS) used shall be recognized by the European Petroleum Survey Group (EPSG). All files shall contain a CRS that is recognized by current industry standard geographic information systems (GIS) software.

The CRS shall be defined in the LAS/LAZ header in Well Known Text (WKT) format. For the definition of WKT, the Branch refers to the Open Geospatial Consortium (OGC) specifications from 2001 [7]. Additionally, the projection shall be defined as a compound coordinate system, including both the vertical and horizontal CRS. See Appendix B: WKT Compound Coordinate System for an example of an acceptable compound CRS in WKT format.

4.1.4 Scale Factor

The scale factor for x, y, and z coordinates in each LAS/LAZ file header shall each be 0.01, indicating centimetre-level precision for coordinate values.

4.1.5 Offset

The offset for x, y, and z coordinates in each LAS/LAZ file header shall be round integers with no non-zero decimal digits.

4.1.6 Global Encoding

Global encoding is a bit field used to indicate certain global properties about a file [6]. The global encoding bit field contains information specifying the type of GPS time and CRS representation in the LAS/LAZ file. If the GPS time is recorded as adjusted standard GPS time and the CRS is represented in WKT format, and no other bits are set, the global encoding value shall be 17 [6]. This value is the accepted, default global encoding value for all LAS/LAZ files submitted to the Branch. For additional information on global encoding values, refer to the ASPRS LAS Specification v1.4 [6].

4.1.7 Point Data Record Format

The Point Data Record Format (PDRF) is a standardized encoding by the ASPRS for identifying attributes of point records in a LAS file. The minimum acceptable PDRF shall be 6, which is the minimum value associated with the ASPRS LAS Specification v1.4 [6].

For standard LAS/LAZ deliverables, the PDRF shall be 6, unless otherwise specified in the project contract. Some circumstances, such as colourization of point clouds, require a PDRF greater than 6. Selection of the PDRF shall be based on the attributes required to represent the dataset. Using an incorrect PDRF will result in a loss of meaningful information, or conversely, increase the size of a file unnecessarily.

Refer to the ASPRS LAS Specification v1.4 for more information about PDRFs [6].

4.1.8 Operation Number Variable Length Record

In every LAS/LAZ file delivered to the Province, there shall be a custom Variable Length Record (VLR) which references the project or operation from which the data was collected. This VLR shall adhere to the ASPRS VLR structure [6].

The VLR shall contain the following information:

User ID	province_bc
Record ID	1
Record Length After Header	0
Description	[Operation Number]

The Operation Number shall be assigned by the Province and cannot exceed 32 bytes. The Operation Number is commonly the same as a contract number (e.g., OP##BMRS###).

4.1.9 System Identifier

The system identifier field in the LAS/LAZ file header shall be populated in all delivered files. The field shall be populated with different entries depending on if the LAS/LAZ file is a raw strip of data, or if it is a tile containing overlapping strips of data.

If the file contains raw LiDAR strip data, the system identifier field shall contain the make and model of the LiDAR system, followed by the serial number of the LiDAR system.

Example: Li-MarkV VQP-15650j; S2223546

If the file contains tiled LiDAR data from overlapping strips, the system identifier field shall contain the make and model from all sensors used within that tile.

Example: SysTech Orion G2000

4.2 Point Cloud Classification

LiDAR point classification shall adhere to the ASPRS standard point classes [6] unless otherwise specified contractually or in this document. Table 2 highlights the minimum required classification for all data submitted to the Province. Additional classes may be required for specific projects.

Outliers, noise points, unreliable points near the extreme edges of the swath, and other points the vendor considers unusable shall be identified using class code 7 and/or 18. This classification applies primarily to unusable or unreliable points that are identified during pre-processing, through automated post-processing routines, during manual classification, or QA/QC.

Table 2: Minimum LiDAR Classification Requirements

Class Code	Description
1	Unclassified[3]
2	Ground
7	Low Point (Noise)
9	Water
17	Bridge Deck
18	High Noise

If overlap points are differentiated by the vendor, they must be identified using a method that does not interfere with their classification, such as assigning a classification flag point attribute bit (i.e., OVERLAP), as described in the article on the ASPRS LAS Specification v1.4 [6]. The technique used to identify these overlap points must be clearly described in the project reports.

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. If running a ground detection routine on a tile, a minimum of 10 metres of data shall be temporarily referenced from adjacent tiles to eliminate errors introduced at the edge of the tile. LiDAR data referenced from adjacent tiles shall not be saved as part of the final tile.

Further instructions regarding classification:

- No points in the LAS/LAZ deliverable shall remain in class code 0.
- Depending on the project requirements, class code 2 (ground) may include other flat surfaces (e.g., roads, parking lots) unless otherwise required in a project contract.
- If only ground and non-ground classes are required, the class code 1 (unclassified) shall be used to classify non-ground points outside of class codes 7 and 18 (noise).
- Any isolated class code 1 further than 3 meters away from at least one other class code 1 point shall be reclassed to class code 7 or 18 before grounding occurs.

[3] ASPRS refers to both classes 0 and 1 as unclassified to maintain compatibility with popular classification software packages [6].

- All points delivered that are between the AOI and BPA shall be classified according to contract and specification requirements.
- There shall be no ground classified points within water bodies larger than 8000 m^2, inside the AOI or BPA.
- Where breaklines are used to delineate water bodies (shorelines), points within those areas shall be classed to class code 9 (water), unless otherwise specified in the project contract.

Point classification shall remain consistent over the entire project, with any variations in the classification between tiles, swaths or lifts being cause for rejection of the deliverable. See to Section 5.6 for further classification accuracy requirements.

4.3 Tiling

All classified LiDAR deliverables shall be tiled, using in the British Columbia Geographic System (BCGS) 1:2500 mapsheet grid system, unless otherwise specified in the project contract. This tiling scheme shall:

- Adhere to naming conventions, provided by the Branch;
- Use the same coordinate reference system and units as the data;
- Edge-match seamlessly and without gaps;
- Include tiles where any BPA coverage exists;
- If multiple isolated project areas fall within a single tile, the data for those areas shall be delivered as a single file.

BCGS tiling shapefiles are provided at the Branch's FTP site. See Section 6.1 for the Branch's FTP site address.

In the case that a project BPA crosses multiple UTM zones, there shall be a single tile of overage into the next UTM zone. This will result in a duplication of a single tile on either side of the UTM zone line in each projection. This is required for LiDAR point cloud data and all LiDAR derived products.

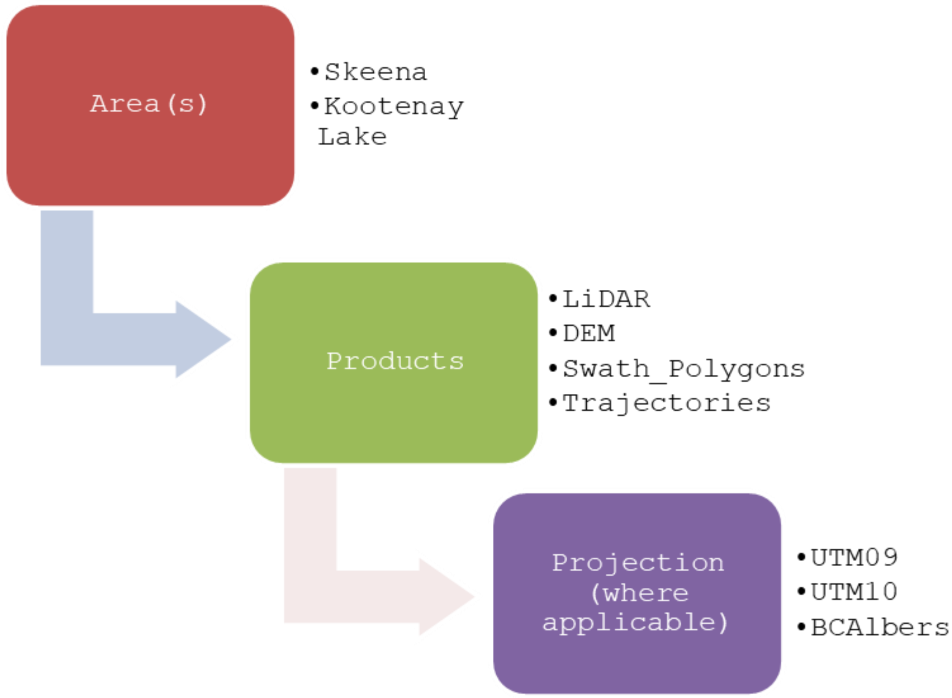
4.4 Data Handling and Shipping

Data shall be delivered on one or more New Technology File System (NTFS) format Universal Serial Bus (USB) 3.0 hard drives, with no less than 2 terabytes (TB) of storage. Drives shall be formatted before use and contain no superfluous files. Submitted storage devices and their packaging shall be labelled at minimum with the following:

- Project name and contract number
    - e.g., “Vancouver Island OP11BMC011”
- Delivery number and date
    - If re-submissions of data occur, include delivery number
- Description of contents
    - A tabulated list of the contained data deliverables

The folder structure of the delivered hard drive shall not contain any spaces in naming, and, where required, use underscores (_) or dashes (-). Folders shall clearly define the product contained (e.g., LiDAR, DEM, DSM, Colourized_Point_Cloud, Trajectories).

Unless stated in the contract, projects consisting of several individual areas on a single hard drive need to be broken down and submitted into area-specific directories containing all data submissions. Where the project is required to be submitted in multiple projections (e.g., UTM and BC Albers) or covers multiple UTM zones, deliverables in each UTM zone shall be submitted in a folder specific that projection (e.g., ‘UTM10’, ‘BCAlbers’). Figure 1 shows the hierarchy of the required folder structure and provides an example.



Example of folder structure for data delivery:

- > Skeena (area)
  - > LiDAR (product)
    - > UTM09 (projection)
      - > All .laz files in UTM09
    - > UTM10 (projection)
      - > All .laz files in UTM 10
  - > Trajectories (product)
    - > All .out trajectory files

Figure 1: Folder structure for data delivery with example

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

5.0 Quality Control Procedures

Quality control (QC) provides systematic, consistent methods of ensuring data integrity, correctness, and completeness. Quality control procedures shall be implemented to provide confidence in datasets delivered. See Section 6.3 for QC reporting requirements.

5.1 LiDAR Quality Level

The Branch requires the Quality Level (QL) of LiDAR data be evenly distributed over the entire project area. The vendor shall adhere to QL2 for all deliverables, unless otherwise specified in the project contract.

5.2 Absolute Vertical Accuracy

The absolute vertical accuracy of a LiDAR data set is considered the fundamental measure of point cloud accuracy. Absolute vertical accuracy shall be assessed using orthometric height and reported in accordance with the ASPRS Guidelines for Vertical Accuracy Reporting for Lidar Data [8].

The required vertical root-mean-square errors ($RMSE_z$) applies to the accuracy assessment of the LiDAR point cloud, reported at 68% confidence level (Table 3). The assessment shall be done on expectedly hard and flat surfaces, which ideally produce single LiDAR returns. The results of the absolute vertical accuracy measurements shall be delivered in an absolute accuracy report. Table 15 in

Appendix A: Accuracy Reporting provides a template for reporting absolute accuracy.

The Branch requires absolute accuracy of LiDAR to be measured using GCPs collected with GNSS during project acquisition. See Section 3.5 for more information on GCP requirements. An acceptable method of testing absolute accuracy involves comparing the vertical, plumbline difference between non-vegetated GCPs and a Triangulated Irregular Network (TIN) surface generated from ground classified LiDAR data. The vertical difference between the GCPs and the plumbline distance to the planar surface of the TIN model can then be measured and reported in terms of $RMSE_z$.

5.2.1 Vertical Accuracy Requirements

Table 3 shows the vertical accuracy requirements for each QL. QL1 represents the highest accuracy and QL5 represents the lowest accuracy. The first column of values in Table 3 are the maximum allowed root-mean-square error ($RMSE_z$) for NVA GCPs, reported at 68% confidence level (CL). The table also shows the accuracy requirements for NVA points at the 95% confidence level, and the limit for VVA points at the 95th percentile. See Section 3.5 for more information on ground control. For more information on accuracy levels, see [9] and [4].

Table 3: Vertical Accuracy Requirements of LiDAR per Quality Level [9], [4]

Quality Level	LiDAR NVA $RMSE_z$ at 68% confidence level	LiDAR NVA at 95% confidence level (NVA $RMSE_z$ * 1.96)	LiDAR VVA at 95th percentile (NVA $RMSE_z$ * 3.00)
QL1	≤ 5.0 cm	≤ 9.8 cm	≤ 15.0 cm
QL2	≤ 10 cm	≤ 19.6 cm	≤ 30.0 cm
QL3	≤ 20 cm	≤ 39.2 cm	≤ 60.0 cm
QL4	≤ 100 cm	≤ 196.0 cm	≤ 300 cm
QL5	≤ 333.3 cm	≤ 653.3 cm	≤ 1000 cm

5.3 Point Density and Spacing

LiDAR point density and spatial distribution requirements shall be considered in the mission design and planning process at a particular flying height within specified parameters referred to in this document as nominal pulse density and spacing (NPD and NPS, respectively). The Branch refers to the net point density and spacing of georeferenced, classified LiDAR point cloud data as achieved ground point density and spacing (AGPD, AGPS).

NPS, AGPS, NPD and AGPD each include only the useable part of a swath (typically 95%), excluding acceptable data voids [4] (see Section 3.6.3).

5.3.1 Density Requirements

Table 4 shows the pulse and point density and corresponding spacing requirements for each QL. See Sections 5.3.2, 5.3.3, 5.3.4, and 5.3.5 for definitions of nominal pulse density (NPD), nominal pulse spacing (NPS), achieved ground point density (AGPD), and achieved ground point spacing (AGPS).

Table 4: Nominal Pulse Density (NPD), Nominal Pulse Spacing (NPS) and Achieved Ground Point Density (AGPD) Requirements per Quality Level

Quality Level	LiDAR NPD (pulse/m^2)	LiDAR NPS (m)	LiDAR AGPD (points/m^2)	LiDAR AGPS (m)
QL1	$\geq$ 12	$\leq$ 0.30	$\geq$ 3.5	$\leq$ 0.53
QL2	$\geq$ 8	$\leq$ 0.35	$\geq$ 3.0	$\leq$ 0.60
QL3	$\geq$ 4	$\leq$ 0.5	$\geq$ 2.0	$\leq$ 0.70
QL4	$\geq$ 2	$\leq$ 0.7	$\geq$ 1.4	$\leq$ 0.84
QL5	$\geq$ 1	$\leq$ 1.0	$\geq$ 1.0	$\leq$ 1.0

LiDAR density shall be primarily assessed using a last return density grid. Ninety-five percent (95%) of last return density grid cells, excluding areas with waterbodies, shall meet the NPD specification for the project QL. See Section 6.8 for more information on the last return density grid deliverable.

LiDAR AGPD shall be primarily assessed using a classified ground density grid. The AGPD value in Table 4 shall be a guideline in areas of canopy. See Section 6.8 for more information on the classified ground density grid deliverable.

5.3.2 Nominal Pulse Density

Nominal pulse density (NPD) as defined by the Branch refers to the total number of emitted LiDAR pulses for single laser sensor, single swath, last-return LiDAR data per square unit of measurement (pulses/area) in mission planning and design.

The project NPD shall meet or exceed the requirements listed in Table 4 for the quality level (QL) assigned to the project.

5.3.3 Nominal Pulse Spacing

Nominal pulse spacing (NPS) as defined by the Branch is the predicted value of the spatial distribution of last return LiDAR points, used as surrogates for pulses, through mission planning and design, represented as units of lateral distance between adjacent surface points. When assessing NPS, it is necessary to measure both along-track and across-track point spacing. NPS can be predicted using flight planning software or calculated as the square root of the average area per last return point. Design of the project NPS shall meet or exceed the requirements listed in Table 4 for the QL assigned to the project.

NPS relates to NPD according to the formula:

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

5.3.4 Achieved Ground Point Density

Achieved ground point density (AGPD) describes the net density of classified ground points. Assessment of the AGPD shall be based on the requirements listed in Table 4 for the QL of the project.

5.3.5 Achieved Ground Point Spacing

Due to the irregular nature of LiDAR scan patterns, achieved ground point spacing (AGPS) represents an average value. Measuring point spacing only at the centre of a swath is not an acceptable method of determining AGPS. AGPS relates to AGPD according to the formula:

$$AGPS = \frac{1}{\sqrt{AGPD}}$$

Assessment of the AGPS shall be made based on the requirements listed in Table 4 for the QL assigned to the project.

5.4 Relative Vertical Accuracy

Relative vertical accuracy refers to the internal geometric precision of a LiDAR dataset without regard to surveyed ground control [4] given multiple flight lines, GNSS conditions, and aircraft attitudes. The Branch considers relative vertical accuracy as the primary measure of the precision of a LiDAR system, as well as a significant indicator of the quality of the LiDAR system calibration. Two primary factors should be considered when testing LiDAR data relative vertical accuracy:

- Smooth surface repeatability (intraswath)
- Overlap/side lap consistency (interswath)

5.4.1 Intraswath Accuracy

Intraswath is a measure of the precision of LiDAR quantified in the assessment of variation (random error) from the single return data of an individual swath on a uniformly flat surface.

This assessment shall be conducted on smooth hard surfaces (e.g., parking lots, rooftops, runways) to determine differences in vertical elevation, where a raster subtraction (calculated using the $RMSD_z$) between a raster generated from minimum elevation and another generated from maximum elevation values using that individual swath from single return point data is performed. These values are not to exceed the acceptable limits of smooth surface repeatability listed in Table 5.

The following method for assessing intraswath accuracy is suggested. If a different method is used, it shall be documented and delivered, along with the sample locations and the results.

Sample areas of approximately 50 square metres will be selected at multiple locations (across and along swath) and shall include areas both at nadir and on the outer swath. The accuracy can then be assessed using a gridded signed difference raster (with cell size equal to 2 times the NPS) derived from the maximum and minimum elevation of the points within each grid cell. The $RMSD_z$ can be calculated using the values of all grid cells of all areas tested.

5.4.2 Interswath Accuracy

Heidemann defines interswath as the "quantified assessment of variations in measurements of a surface that, under ideal theoretical conditions, would be without variation" [4]. Swath overlap or side lap consistency is a measure of geometric alignment of two overlapping swaths and is a fundamental measure of the quality of the sensor adjustment of the data from each lift; this measure of geometric alignment can also be applied to overlapping lifts and project AOIs.

For internal assessment of interswath accuracy, the Branch refers to its proprietary program, LiCal©. LiCal© is based on the data quality measures (DQMs) from the ASPRS Guidelines on Geometric Inter-Swath Accuracy and Quality of LiDAR Data [10], while also implementing statistical hypothesis testing for evaluating acceptance or rejection criteria of overlapping LiDAR data. LiCal© is available to vendors at the Branch's FTP site. See Section 6.1 for the Branch's FTP site address.

If any other method(s) of testing overlap/side lap consistency are used, the following criteria of assessment shall be considered:

- Multiple locations within adjacent, overlapping, parallel swaths, in non-vegetated areas of only single returns.
- Areas should include planar surfaces of varying slope and aspect, not only level surfaces.
- Assessment should include cross tie swaths.

The methodology used in determining the interswath accuracies of a dataset, such as those outlined in the USGS LiDAR Base Specification [4], shall be part of the deliverables and results shall comply with the requirements listed in Table 5.

Table 5: Relative Vertical Accuracy Requirements

Quality Level	Smooth surface repeatability $RMSD_z$ (cm)	Swath overlap difference $RMSD_z$ (cm)	Swath overlap maximum differences allowed (cm)
QL1	≤ 3.0	≤ 4.0	± 8.0
QL2	≤ 6.0	≤ 8.0	± 16.0
QL3	≤ 12.0	≤ 16.0	± 32.0
QL4	≤ 24.0	≤ 32.0	± 64.0
QL5	≤ 48.0	≤ 64.0	± 64.0

5.5 Absolute Horizontal Accuracy

Evaluating absolute horizontal accuracy of LiDAR data presents greater challenges than vector-based or digital orthophoto products. Features that are visible in traditional imagery are more difficult to identify in products created from LiDAR data.

Comparing overlapping areas of adjacent flight lines can help identify some relative horizontal accuracy (precision) errors in LiDAR data. However, some horizontal errors will not be discernible in this comparison.

Similarly, measuring absolute vertical accuracy provides an opportunity to observe major horizontal errors, but smaller horizontal errors may be missed, as vertical accuracy is assessed using relatively level surfaces.

The following sections, 5.5.1 and 5.5.2, outline some methods of measuring absolute horizontal accuracy. Regardless of the strategy used, it should include different planes, not only level surfaces. If performed, a description of the method used to measure absolute horizontal accuracy, and its results shall be included with project deliverables.

5.5.1 Indirectly Measured Absolute Horizontal Accuracy

Different methods may be used to measure absolute horizontal accuracies. Two of these methods are outlined below.

The first method, as described by Meade [11], involves selecting features during a ground control field survey in which horizontal position can be precisely measured and compared with intensity images generated from the LiDAR data. For example, painted strips in parking lots could be used as control points due to their high reflectivity and contrast to the surrounding asphalt.

Another method described by Meade [11] to find horizontal variation is to compare the coincidence of cross-sections measured using ground survey techniques against cross-sections generated from a TIN created with the LiDAR data. Again, the ground survey measurements should be done in areas showing significant slope, not only on level surfaces, and in different orientations. Roadway ramps, embankments or levees are considered appropriate areas for cross-section measurements.

5.5.2 Directly Measured Absolute Horizontal Accuracy

Directly measured horizontal and vertical LiDAR accuracies can be obtained by using spatially oriented target control boxes. These targets consist of a box (e.g., cardboard or plywood) with orthogonal sides. The box faces are spatially aligned in three dimensions with the coordinate axes of the LiDAR data (e.g., northing, easting, and elevation axes in UTM). The box faces are surveyed using traditional survey methods to obtain coordinates for those planes (X_{Target} and Y_{Target} in Figure 2).

LiDAR coordinate errors in easting (ΔX) can be obtained by subtracting the known coordinate X_{Target} represented by the YZ plane (northing/elevation face of the target) from a LiDAR coordinate X_{LiDAR}. Similarly, coordinate errors in northings (ΔY) can be obtained by subtracting the known coordinate Y_{Target} from the XZ plane (easting/elevation face of the target) in the LiDAR data. Figure 2 shows the spatial orientation of these target boxes and measurement points.

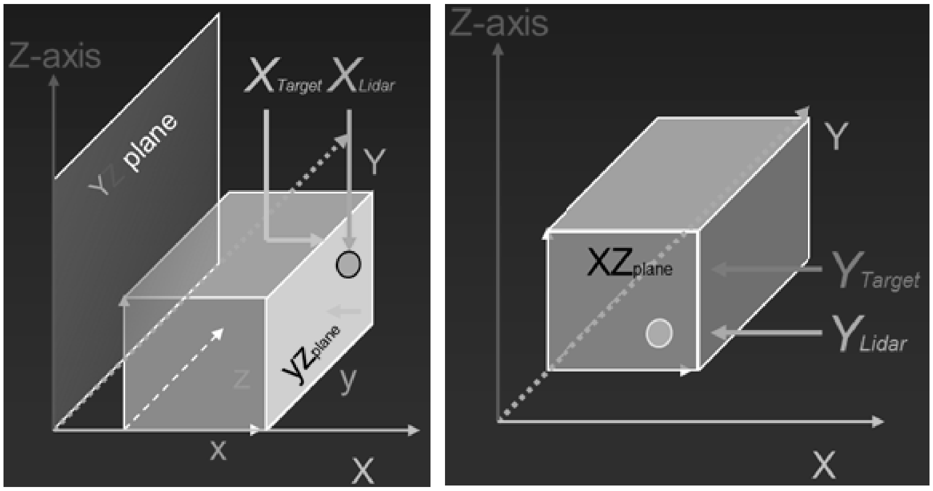


Figure 2: Measuring absolute horizontal accuracy with a plane of lidar points
compared to an independent point measurement of the same plane

Depending on the number of LiDAR points falling on the target plane, the 1-dimensional RMSE at 68% probability for each coordinate axis can be obtained according to:

$$RMSE_{coordinate} = \sqrt{\sum \frac{\left(N_{plane} - N_i'\right)^2}{n}} \qquad \text{(1dRMSE, at 68\% probability)}$$

where:

N_{plane} is the specific measured target box coordinate for a target sidewall, plane specific

N_i' is the i^{th} corresponding LiDAR point coordinate of the sidewall (plane) being evaluated

i is an integer ranging from 1 to n, and

n is the number of LiDAR point hits on the specific sidewall (plane)

5.5.3 Linear Horizontal Error Model

In addition to the above methods, the Branch suggests the following linear error propagation model to estimate the LiDAR a priori horizontal accuracy:

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

where:

$RMSE_r$ is the horizontal LiDAR point accuracy over flat terrain at 63% probability (metres)

θ_{laser} is the laser beam divergence (milliradians)

$\sigma_{GNSS_{xy}}$ is the average horizontal positional precision of the GNSS system at 63% probability (metres). Largest term; approximates $RMSE_r$.

$\sigma_{IMU_{rp}}$ is the average angular accuracy of the drift-corrected IMU in roll and pitch orientations (milliradians)

AGL is the flying height above ground (metres).

5.6 Classification Accuracy and Errors

Classification accuracy is a measure of errors related to classification. The Branch considers classification errors to be any points that are not in the appropriate required class.

5.6.1 Classification Errors

Some examples of classification errors include but are not limited to:

- Any area where a required appropriate class code is not used (e.g., trees not classified into high vegetation class code 5).
- Features incorrectly included in a class code (e.g., cars, buildings/rooftops included in high vegetation class code 5).
- Ground points found in non-ground features (e.g., trees, overhanging branches).

5.6.2 Classification Error Testing

The Branch tests for classification accuracy on randomly selected tiles throughout the project AOI. When classifying data, attention should be given to areas which are susceptible to classification errors (e.g., sudden changes in terrain where classification parameters have not been adjusted accordingly), including searching for points that have demonstrable classification errors.

Table 6 indicates the acceptable percentage of tiles from the set randomly selected for QC that may contain with errors, which do not include the automatic-rejection errors listed in Section 5.6.3. A tile is in error when one or more classification errors are identified. Exceeding the values shown in Table 6 shall be considered by the Branch as grounds for rejection of the entire dataset.

Table 6: Classification Errors per Quality Level

Quality Level	Percentage of QC tiles with classification errors
QL1	≤ 1%
QL2	≤ 5%
QL3	≤ 10%
QL4 and QL5	≤ 15%

5.6.3 Causes for Automatic Rejection of LiDAR Data

The following classification errors shall result in automatic rejection of the dataset:

- An excess or high density of misclassified points. Misclassification is considered in excess as identified by the Branch.
- Valid project points classified as noise or withheld, or conversely, points classified as valid project classifications that should be identified as noise or withheld.
- A required class code is not included in the dataset.
- Duplicate points within the datasets (two or more points with the same coordinates and timestamps).
- Thinned, interpolated, smoothed, or artificial points, unless specified in the project contract.
- Ground points within waterbodies larger than 8000 m^2 or within rivers that have an average width greater than 30 m.

- Noticeable inconsistency in character, texture, density, or quality of the classification between tiles, swaths, lifts, or other non-natural divisions of data.
- Multiple files delivered for a single tile, for example, if the tile contains multiple isolated project areas. If multiple isolated project areas fall within a single tile, the data for those areas shall be delivered as a single file.

6.0 Project Deliverables

This section outlines the LiDAR deliverables and supporting documents the Branch expects during milestones of a LiDAR project, unless otherwise specified in the project contract.

A project kickoff meeting shall be held between the Branch and the vendor before data acquisition to ensure that project requirements and schedule are mutually understood.

6.1 Templates and Resources

The Branch maintains a file transfer protocol (FTP) site containing templates and resources for LiDAR projects, including:

- Quality control report forms for acquisition and production data
- Metadata summary form and templates
- Tiling grid spatial files
- LiCal© propriety software for assessing interswath accuracy and system calibration

The FTP site with these resources can be accessed at:

- **ftp://ftp.geobc.gov.bc.ca/sections/outgoing/dis/**

6.2 LiDAR Data Submission and Reporting

Table 7 outlines the timeline for data submission and reporting requirements. All deliverables shall adhere to file naming conventions provided by the Branch.

Acquisition shall not begin until the Branch reviews and approves all planning deliverables, as outlined in Table 7.

Table 7: LiDAR Data Submission Reporting Requirements

<table>
<tr><th colspan="6">LiDAR Data Submission Reporting Requirements</th></tr>
<tr><th colspan="6">1. Planning Deliverables</th></tr>
<tr><th>Milestone</th><th>Reference section</th><th>Product</th><th>Format</th><th>Number of copies</th><th>Notes</th></tr>
<tr><td rowspan="4">Prior to Acquisition</td><td>6.4.2</td><td>LiDAR system calibration report</td><td>.doc or .pdf</td><td>1</td><td>Acquisition shall not begin until review and approval of calibration report</td></tr>
<tr><td>6.4.1</td><td>LiCal© output reports</td><td>.pdf and .csv</td><td>1</td><td>Acquisition shall not begin until review and approval of LiCal© output reports</td></tr>
<tr><td>6.6</td><td>Mission planning report</td><td>.doc or .pdf</td><td>1</td><td>Acquisition shall not begin until review and approval of Mission Planning Report</td></tr>
<tr><td>3.2</td><td>LiDAR calibration data (raw)</td><td>.laz 1.4</td><td>1</td><td>Acquisition shall not begin until review and approval of LiDAR Calibration outcome</td></tr>
<tr><th colspan="6">2. Flight Reporting</th></tr>
<tr><th>Milestone</th><th>Reference section</th><th>Product</th><th>Format</th><th>Number of copies</th><th>Notes</th></tr>
<tr><td>During Acquisition</td><td>6.7</td><td>Flight report</td><td>Online Acquisition Reporting System (web-based GIS map)</td><td>n/a</td><td>Updated daily</td></tr>
<tr><th colspan="6">3. Acquisition Deliverables</th></tr>
<tr><th>Milestone</th><th>Reference section</th><th>Product</th><th>Format</th><th>Number of copies</th><th>Notes</th></tr>
<tr><td rowspan="8">Six Weeks Past Acquisition</td><td>6.10</td><td>Trajectories (SBET)</td><td>.out</td><td>1</td><td></td></tr>
<tr><td>6.3.1</td><td>Calibrated, unclassified strip-adjusted LiDAR</td><td>.laz 1.4</td><td>1</td><td></td></tr>
<tr><td>6.3.1</td><td>Calibrated, unclassified strip-adjusted LiDAR QC report</td><td>.pdf</td><td>1</td><td></td></tr>
<tr><td>6.8</td><td>Last return density grid</td><td>GeoTIFF</td><td>1</td><td>Raster values shall be float data types</td></tr>
<tr><td>6.9</td><td>LiDAR swath extent polygons</td><td>shapefile</td><td>1</td><td></td></tr>
<tr><td>6.12</td><td>GNSS survey report</td><td>.doc or .pdf</td><td>1</td><td></td></tr>
<tr><td>6.13</td><td>GNSS point data</td><td>shapefile</td><td>1</td><td></td></tr>
<tr><td>6.14</td><td>LiDAR data adjustment report</td><td>.doc or .pdf</td><td>1</td><td></td></tr>
</table>

4. Production Deliverables					
Milestone	Reference section	Product	Format	Number of copies	Notes
Four Weeks Prior to Project Deadline	5.6	Classified LiDAR point cloud	.laz 1.4	2	
	6.3.2	Classified LiDAR point cloud QC report	.pdf	1	
	6.8	Classified ground density grid	GeoTIFF	2	Raster values shall be **float** data types
	n/a	Digital Elevation Model	GeoTIFF	2	See GeoBC DEM Specifications for more detail
	n/a	Digital Surface Model	GeoTIFF	2	See GeoBC DEM Specifications for more detail
	n/a	Shoreline delineation	shapefile	1	Based on LiDAR intensity data; see GeoBC DEM Specifications for more detail
	4.3	Tiling grid	shapefile	1	
	6.5	Metadata reports	PDF	1	One PDF file, templates provided by the Branch
	6.11	Final production coverage	GeoPackage	1	
5. Post-Production Deliverables					
Milestone	Reference section	Product	Format	Number of copies	Notes
Post Production	6.15	Final project report	.doc or .pdf	1	

6.3 Quality Control Reports

Quality control reports for both acquisition and processed (production) data are mandatory for all projects. Requirements for these reports are described in the following subsections.

6.3.1 Acquisition Data Quality Control Report

Table 8 outlines the requirements for Quality Control reporting for calibrated, unclassified strip-adjusted (acquisition) LiDAR data. A template for this report is provided by the Branch at the Branch's FTP site. See Section 6.1 for the Branch's FTP site address.

Table 8: Acquisition Data Quality Control Report Requirements

Acquisition Data Quality Control Report			
Project name:			
Contract number:			
Date of submission:			
Produced by:			
Product	Reference in specification	Check	Requirement
Calibrated, Unclassified, Strip-Adjusted LiDAR	3.6.2	Swath side lap/overlap	≥ 30%
	3.6	Buffered project area (BPA)	≥ 100 m
	4.1	Data format	.laz 1.4
		Flight line numbers	Present and unique for all flight lines
	4.1.2	GPS time	Adjusted Standard GPS Time, present in all points
	4.1.3	CRS information	Projection
			Horizontal datum: NAD83 (CSRS)
			Vertical datum: CGVD2013
			Geoid model: CGG2013
			compound WKT format (horizontal and vertical datum) georeferencing Information in LiDAR file headers
	4.1.8	Operation # VLR	Operation Number VLR in every LAS/LAZ file
	4.1.4	Scale factor x y z	0.01 0.01 0.01
	4.1.5	Offset x y z	Integers; no non-zero decimal digits
	4.1.6	Global encoding value	17
	4.1.9	System identifier	Consistent & appropriate values set for every tile delivered
	Conventions provided by the Branch	Naming convention	Adherence to naming conventions

6.3.2 Classified Data Quality Control Report

Table 9 outlines the requirements for the Quality Control Report for classified (production) LiDAR data. A template for this report is provided by the Branch at the Branch's FTP site. See Section 6.1 for the Branch's FTP site address.

Table 9: Classified LiDAR Quality Control Report Requirements

Production LiDAR Quality Control Report			
Project name:			
Project number:			
Date of submission:			
Produced by:			
Product	**Reference in specification**	**Check**	**Requirement**
Classified LiDAR Point Cloud	4.1.7	Return fields	Conforming to ASPRS Point Data Record Formats [6], unless otherwise specified in project contract
	4.2	Classification	Classes: 1, 2, 7, 9, unless otherwise specified in project contract
	4.1.3	CRS information	Projection
			Horizontal datum: NAD83 (CSRS)
			Vertical datum: CGVD2013
			Geoid model: CGG2013
			Compound WKT format (horizontal and vertical datum), georeferencing information in LiDAR file headers
	4.3	Tiling	1:2500 BCGS
	4.1	Data format	.laz 1.4
	4.1.4	Scale factor x y z	0.01 0.01 0.01
	4.1.5	Offset x y z	Integers; no non-zero decimal digits
	4.1.6	Global encoding value	17
	4.1.8	Operation # VLR	Operation number VLR in every LAS/LAZ file
	4.1.9	System identifier	Consistent and appropriate values set for every tile delivered
	5.2	Absolute vertical accuracy	$\leq$ 10 cm at $RMSE_z$[4]
	3.5.3	Number of GCPs used to assess absolute vertical accuracy	If strip adjustment: 10 GCPs per isolated project area; if no strip adjustment, 20 GCPs per isolated project area
	5.4.1	Smooth surface repeatability	$\leq$ 6 cm $RMSD_z$[5]
			Provide flight line numbers tested
	5.4.2	Interswath accuracy	$\leq$ 8 cm $RMSD_z$[5]
			Provide pairs of flight line numbers tested
	Conventions provided by the Branch	Naming convention	Adherence to naming conventions

[4] Value references QL2 in Table 3 (p. 25) and is subject to change dependent on project Quality Level.
[5] Values reference QL2 in Table 5 (p. 29) and are subject to change dependent on project Quality Level.

6.4 System Calibration Report

A LiDAR system calibration report is required to provide details on the airborne survey equipment proposed for the project. For projects utilizing multiple scanning systems and multiple aircrafts, a LiDAR system calibration report is required for each system installation in each aircraft. Any sensor changes, failures, or replacements prior to or during the data collection shall be reported to the Branch once identified. For LiDAR system calibration guidelines, see Section 3.2.

6.4.1 LiCal© Outputs

Vendors shall use the Branch's proprietary program LiCal© on the calibration LiDAR swaths and deliver all the outputs. The vertical RMSD threshold shall adhere to the appropriate project QL value found in Table 5 (p. 30), and the horizontal RMSE threshold shall refer to the theoretical horizontal accuracy ($RMSE_r$) of the LiDAR system (see Section 5.5.3). All outputs (.pdf files and a .csv) shall be submitted along with the calibration report. LiCal© is based on the Data Quality Measures (DQMs) from the ASPRS Guidelines on Geometric Inter-Swath Accuracy and Quality of LiDAR Data [10].

6.4.2 System Calibration Report

The Branch may provide a LiDAR Calibration Report template for vendor use, including pertinent LiDAR system calibration information. If a vendor submits a LiDAR system calibration report that differs from the Branch template, the document shall include at a minimum the information listed in Table 10.

Table 10: Minimum Requirements for LiDAR Calibration Report

Components	Requirements

Sensor instrument – LiDAR system	• System information
	  ○ Manufacturer, model, year
	  ○ Laser beam divergence (reported at $1/e^2$)
	  ○ Ownership
	  ○ Serial number
	• Sensor properties
	  ○ Scanning mechanism
	  ○ Maximum pulse repetition frequency (PRF) & scan rate
	  ○ Field of view
	  ○ Maximum operating flight altitude AGL
	  ○ Laser channel offset (if applicable)
	• Processing/logging software

Airborne positioning system (GNSS/INS)	• System information
	  ○ Manufacturer, model, year
	  ○ Serial number
	• Performance specifications
	  ○ Horizontal & vertical positional accuracy
	  ○ GNSS logging frequency
	  ○ IMU logging frequency
	  ○ True heading
	  ○ Roll and pitch
	• Processing software
	• Processing solution/method
	  ○ Lever arm distances
	• GNSS flight conditions
	  ○ Maximum and minimum number of satellites
	  ○ Maximum and minimum PDOP
	  ○ Vertical dilution of precision (VDOP)

CRS information	• Horizontal datum • Vertical datum • Epoch transformation • Projection system • Geoid
Ground control points (for the purpose of calibration)	• GNSS ground survey methodology • Instrument model, and manufacturer precisions • Ground control points' coordinates • LiDAR data comparison to control

Calibration results	• Calibration procedure and method
	• Full LiCal© output reports (.pdf and .csv)
	  ○ Include contract number in company name
	• Calibration flight parameters
	• Calibration date and site
	• Lever arm offsets
	• Roll, pitch, yaw, and scanner scale factors
	  ○ Pre- & post-adjustment
	• Adjustment parameters
	  ○ Software outputs of adjustment
	• Least-squares adjustment report (if applicable)
	  ○ Variance-covariance matrix of calibration parameters
	  ○ Flight line ID and best estimated trajectory

6.5 Metadata

A PDF metadata summary shall be submitted with all projects. Templates will be provided via the Branch's FTP site. See Section 6.1 for the Branch's FTP site address.

Table 11 shows the information required in the PDF form. Refer to conventions provided on the FTP site for file naming conventions.

Table 11: LiDAR Metadata Summary Requirements

LiDAR Metadata Summary			
Owner:		Date of submission:	
Project name:		Contract number:	
Project location:			
Acquisition			
Specifications (select from list or enter alternate):			
Range of acquisition dates:		GeoBC quality level:	Project units:
Sensor model(s):		Planned flying height above ground level (AGL) (metres):	m
Maximum returns:		Planned flying speed (knots):	kn
Maximum scan angle (FOV)	°	Planned swath width (metres):	m
Pulse rate (hertz):	Hz	Swath overlap/side lap (percentage each side of swath):	%
Beam divergence (milliradians):	mrad	Planned nominal pulse density (NPD) (pulses per square	pulses/m^2
Format			
LAS version:		LAS synthetic flag used?	
Global encoding value:		LAS key-point flag used?	
LAS Point Data Record Format (PDRF):		LAS withheld flag used?	
Scale factor (x, y, z):		LAS overlap flag used?	
Classification			
Classified?			
Class codes used:			
Achieved Accuracy			
Non-vegetated vertical accuracy (NVA) (95% confidence level, [1.96*$RMSE_Z$]) (centimetres):	cm	Vegetated vertical accuracy (VVA) (95th percentile [3.00* $RMSE_Z$]) (centimetres):	cm
Number of NVA ground control points (GCPs):		Number of VVA GCPs:	
Interswath accuracy (RMSD) (centimetres):	cm	Intraswath accuracy (RMSD) (centimetres):	cm
Number of flight line pairs tested for interswath accuracy:		Number of flight lines tested for intraswath accuracy:	
Reference System			
Horizontal datum:		Projection system(s):	
Vertical datum:		Geoid model:	
Derived Products		**Additional Notes (optional)**	
☐ DEM ☐ DSM ☐ Other (specify):			

6.6 Mission Planning Report

The following indicates the minimum content of the mission planning report:

- Important project dates:
    - Start of collection
    - Vegetation conditions (leaf-on/off)
    - Timeline for deliverables
    - Final project deadline
- Aircraft information
    - Make, model and tail number of all aircraft
    - Airport staging information
    - Assessment of controlled airspaces where special permits may be required (if applicable)
- Calibration plan
- Flight planning
    - Maps which include:
        - Planned survey area and buffer
        - Flight line locations
    - Flight line overlap
    - Flying height AGL
    - Flying speed
    - Scan rate
    - Scan field of view
    - Point density and spacing estimations
        - See Sections 6.3.1, 6.4.2
- Planned GNSS reference stations and control points
- Planned fieldwork procedure
- Planned procedure for re-flights
- Planning to account for weather, land cover, and terrain
- Tidal considerations, if applicable

6.7 Flight Report

Project information and flight logs shall be reported in the Online Acquisition Reporting System (OARS) provided by the vendor. The required content of the flight report is listed below and shall be updated daily:

- Date of collection
- Pilot and operator names
- Aircraft make, model and tail number
- Extent of collection
- Weather conditions
- Ground conditions
- Any problems encountered

The OARS provided shall include visual representations including but not limited to:

- Planned acquisition flight lines
- Accepted acquired flight lines
- Flight lines requiring re-flight

6.8 Density Grids

The following subsections describe density grid requirements.

6.8.1 Density Grid Deliverables

Two density grids shall be delivered: a last return density grid delivered with acquisition deliverables, and a classified ground density grid included with production deliverables.

6.8.1.1 Last Return Density Grid

A density grid generated from last return data only, as surrogates for pulses, shall be delivered with acquisition deliverables.

The last return density grid will be used to verify:

- Data acquisition and area coverage
- Achieved pulse density

See Section 5.3.1 for more information on pulse density requirements.

6.8.1.2 Ground Density Grid

A density grid generated from points classified as ground shall be delivered with production deliverables. The ground density grid will be used to verify that achieved ground point density (AGPD) meets specifications.

See Section 5.3.1 for more information on AGPD requirements.

6.8.2 Density Grid Format

The last return density grid and the classified ground density grid shall be delivered according to the following specifications.

6.8.2.1 File Type

Density grids shall be delivered as GeoTIFF files. Each density grid may be a single file representing the entire collected area, or multiple files representing each isolated project area.

6.8.2.2 Data Represented in Density Grids

Density grids shall be generated for the entire AOI and BPA and represent data from all swaths.

6.8.2.3 Density Grid Resolution

Density grids shall be rasters with five-metre resolution, such that each cell is a square with an area of 25 square metres. The value at each raster cell shall indicate the density of points per square metre within that cell. Density values shall be reported to at least one decimal place precision.

$$Density\ value\ for\ single\ raster\ cell = \frac{Number\ of\ points\ in\ cell}{Area\ of\ cell}$$

- For example, if there are 500 points within a five-by-five-metre raster cell, the cell has a density of 20.0 points per square metre (500 points divided by 25 square metres).

6.9 LiDAR Swath Extent Polygons

For each LiDAR swath collected, a georeferenced polygon (shapefile) representation of the swath extents shall be delivered. Each polygon shall generally follow the overall shape of the swath. Bounding box rectangles and other simplified rectangles are not acceptable.

Each polygon shall be delivered in shapefile format using the same projection and name as the acquired LiDAR data it bounds (see naming conventions provided by the Branch). Additionally, each polygon shall contain the attributes listed in Table 12.

Table 12: LiDAR Swath Extent Polygon Attributes

Attribute Field Name	Field Type	Description
LIDAR_SYS	Text	Name of the LiDAR System used to acquire the data (e.g., Riegl VQ-780i)
SYS_SN	Text	Serial Number of the LiDAR System used to acquire the data
ACQ_DATE	Text	Date of data acquisition, format YYYY-MM-DD (e.g., 2022-04-19)
AGL	Integer	Flying height above ground level (AGL) during acquisition in metres
PRF	Integer	Effective pulse repetition frequency (PRF) during data collection in hertz

6.10 Flight Trajectories

Flight trajectories of the acquisition mission, represented by a smoothed best estimate of trajectory (SBET), shall be submitted to the Branch according to the timelines set out in Section 6.1. Trajectory files shall be delivered in .out file format. The complete, unclipped SBET file shall be provided at the request of the Branch.

6.11 Final Production Coverage

Final coverage shall be delivered as a georeferenced multipolygon to indicate the full classified LiDAR coverage extents for the project.

The final production coverage file:

- Shall be delivered in GeoPackage file format, consistent with the most recent GeoPackage Encoding Standard [12]
- Shall only include areas of accepted classified LiDAR, as these extents may differ from the proposed or acquired coverage.
- Shall be delivered as a single file, projected in BC Albers [EPSG:3005]
- Shall be clipped to the project AOI, not the BPA.
- Features shall be dissolved, showing a single polygon for each AOI with no overlapping features/polygons.
- Shall be named according to naming conventions provided by the Branch and contain the attributes shown in Table 13.

Table 13: Final Production Coverage Attributes

Attribute Field Name	Field Type	Description
year_of_acquisition	Integer	Year of project acquisition (e.g., 2022)
contract	Text	Contract number (e.g., OP22BMRS099)
project_name	Text	Name of project spelled out entirely (e.g., BCTS TPG-TSK)
status_of_completion	Text	Either "**Complete**" or "**Incomplete**"
site_name	Text	Name of project site polygon
area_sqkm	Double/Real	Calculated area in square kilometres
source	Text	"**BC Government**"
contractor	Text	Data provider company name
density	Integer	Design density of the project
status_of_availability	Text	-- Please leave empty --

6.12 GNSS Survey Reports

GNSS survey reports shall include information on all GNSS survey points collected.

GNSS survey reports shall include:

- Instrumentation
    - Instrument model
    - Manufacturer precisions
    - Instrument calibration results (if applicable)
- CRS information
    - Horizontal and vertical datum, including horizontal epoch reference
    - Geoid model

- Projection
- Information for all collected points
  - Coordinates
  - Final accuracies
    - Vertical RMSE ($RMSE_z$) (68%)
    - Horizontal RMSE ($RMSE_r$) (63%)
  - Type of reference station used (i.e., CBN, CACS, BCACS, or PPP point)
  - Reference station coordinates
  - Digital images of control points, if marked, with point identification information
- Detailed explanation of processing method (i.e., Precise Point Positioning or differential processing, and any additional processing methods)
- Processing report
  - Software or application used
  - All input parameters
  - Full output results for all collected points
  - All default reports generated by the software used for processing
- Adjustment report (if applicable)
  - Software or application used
  - All input parameters (i.e., precision weighting, a priori scale factor, etc.)
  - Full output results
  - All default reports generated by the software used for adjustment
- Signature by a designated professional (geomatics technologist, land surveyor, geomatics engineer)

6.13 GNSS Point Format

All GNSS points collected, including passive vertical control points and GCPs shall be delivered to the Branch as a single georeferenced point shapefile. Geodetic reference station points (CACS, BCACS, and CBN points) shall not be included in the shapefile. GNSS point shapefiles shall be named according to naming conventions provided by the Branch and delivered according to the timelines outlined in Section 7.1.

Table 14 shows the formatting and field requirements for GNSS points.

Table 14: GNSS Point Attributes

Attribute Field Name	Field Type	Description
point_id	Text	Name or ID of point. Value shall be unique and persistent. • If the point is a passive vertical control point collected on a MASCOT GCM, the POINT_ID value shall have the format **GCM#**, where # is the MASCOT GCM number. ○ e.g., GCM471920
obs_date	Text	Local date of GNSS observations, in format **YYYY-MM-DD**, e.g., 2022-04-19
contract	Text	Project contract number, e.g., OP22BMRS024
gc_type	Text	Either "**NVA**" (non-vegetated) or "**VVA**" (vegetated). See Section 3.5.1.
descrip	Text	Description of marker • e.g., nail, paint line, cut block, brass cap, no mark • If the point is a passive vertical control point collected on a MASCOT GCM, the DESCRIP value shall be **MASCOT**
checkpoint	Text	**"check"** if used as verification point in accuracy assessment of the LiDAR data, otherwise null
processing	Text	Processing type used (RTK, PPK, PPP, etc.)
h_v_datum	Text	Define the horizontal datum (epoch) and vertical datum, separated with "/" • e.g., NAD83(CSRS)v4e2002/CGVD2013
geoid	Text	Name of geoid model (**CGG2013**)
projection	Text	UTM zone, in the format **UTMz##** (where ## is zone number, e.g., UTMz09)
coord_e	Float	UTM easting coordinate in metres to 3 decimal places
coord_n	Float	UTM northing coordinate in metres to 3 decimal places
coord_ht	Float	CGVD2013 orthometric height coordinate in metres to 3 decimal places
stdev_e	Float	Standard deviation of easting in metres to 3 decimal places
stdev_n	Float	Standard deviation of northing in metres to 3 decimal places
stdev_ht	Float	Standard deviation of orthometric height in metres to 3 decimal places

6.14 LiDAR Data Adjustment Report

If any data adjustments are performed, the vendor shall submit a data adjustment report which includes the following:

- Software or application used
- Detailed explanation of methodology
- All input parameters
- Full output results

6.15 Project Report

A project report shall be delivered no more than two weeks after products are delivered at the end of the LiDAR project. The project report serves as the main report for the entire project. The project report shall be signed by an authorized representative.

The project report shall include the following sections:

- Project Summary
    - Provide summary of location, area size and coverage, and dates.
- Acquisition
    - Provide summary of aircraft, system information and system installations.
- Calibration
    - Provide summary of calibration site, methodology and processing details.
    - Full calibration report in an appendix
- Airborne Positioning System Processing
    - Provide summary detailing the GNSS/INS processing, including software and methodology.
- Post-Processing
    - Provide summary of adjustment methodology, software, and results.
- Production
    - Provide summary of tile scheme, data acquired, and derived products.
- Geodetic Frame and Ground Control
    - Provide summary of equipment, method of collection, data processing, datum, projection, and geoid.
    - Include full GNSS survey report (see Section 7.12)

- Density QC
    - Last return and ground point density statistics (including histogram plots)
    - Last return and ground density rasters (see Section 6.8)

- Accuracy QC
    - Absolute accuracy: provide summary of accuracy testing methodology (e.g., point-to-point or point-to-plane comparison), and results achieved. See Appendix A: Accuracy Reporting for accuracy reporting templates.
    - Relative accuracy: Provide methods summary and results.

6.16 File Naming Conventions

Naming conventions for all deliverables are provided at the Branch’s FTP site. See Section 6.1 for the Branch’s FTP site address.

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[11] M. E. Meade, "From the Ground Up: Horizontal Accuracy Assessment in LiDAR," 2008.

[12] "GeoPackage Encoding Standard," Open Geospatial Consortium, [Online]. Available: https://www.ogc.org/standard/geopackage/.

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Appendix A: Accuracy Reporting

Vertical accuracies of LiDAR data shall be reported using Table 15 as a template. Equations used to calculate values in accuracy reports are listed later in this appendix.

Table 15: Absolute Vertical Accuracy Report for LiDAR Data

Absolute Vertical Accuracy Report for LiDAR Data					
Point ID	Measured values (LiDAR) [metres, 3 decimal places]	Survey control point values [metres, 3 decimal places]			Measured error [metres, 3 decimal places]
	Elevation (orthometric) (z)	Easting (x)	Northing (y)	Elevation (orthometric) (z)	Δ_z Elevation
GCP1					
GCP2					
GCP3					
…					
GCPn					
Number of elevation control points					
Mean error					
Standard deviation					
Root-mean-square error ($RMSE_z$); 1d-RMSE at 68% confidence level					

If horizontal accuracies of LiDAR data are assessed, they shall be reported using Table 16 as a template. Equations used to calculate values in accuracy reports are provided later in this appendix.

Table 16: Absolute Horizontal Accuracy Report for LiDAR Data

Absolute Horizontal Accuracy Report for LiDAR Data						
Point ID	Measured values (LiDAR) [metres, 3 decimal places]		Survey control point values [metres, 3 decimal places]		Measured error [metres, 3 decimal places]	
	Easting (x)	Northing (y)	Easting (x)	Northing (y)	Δ_x Easting	Δ_y Northing
GCP$_x$1						-
GCP$_x$2						-
GCP$_x$3						-
…						-
GCP$_x n$						-
GCP$_y$1					-	
GCP$_y$2					-	
GCP$_y$3					-	
…					-	
GCP$_y m$					-	
Number of (easting, northing) control points						
Mean error						
Standard deviation						
Root-mean-square error ($RMSE_x$, $RMSE_y$); 1d-RMSE at 68% confidence level						
Root-mean-square error ($RMSE_r$); horizontal RMSE at 63% confidence level						

Equations used to calculate the values in accuracy reports:

residual errors

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

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

n is the number of control points

mean error

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

where:

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

i is an integer ranging from 1 to n and

n is the number of control points

standard deviation

$$\sigma = \sqrt{\sum \frac{\left(\Delta_i - \overline{\Delta}\right)^2}{(n-1)}}$$

where:

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

$\overline{\Delta}$ is the mean error in the specified direction

i is an integer ranging from 1 to n and

n is the number of control points

root-mean-square error

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

where:

N_i is the ith 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 is the number of control points

radial horizontal accuracy

$$RMSE_r = \sqrt{RMSE_x^2 + RMSE_y^2} \qquad \text{(horizontal RMSE, at 63\% probability)}$$

where:

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

$RMSE_y$ is the RMSE in the y-direction

Appendix B: WKT Compound Coordinate System

The Branch recommends gdalsrsinfo (https://gdal.org/programs/gdalsrsinfo.html) for verification of correctly formatted WKT CRS. The following is an example of what the Branch considers a valid WKT:

gdalsrsinfo -o wkt1 EPSG:3157+6647

[EPSG (3157 + 6647): NAD83 (CSRS) / UTM zone 10N + CGVD 2013(CGG 2013) height]

Corresponding Open Geographic Consortium (OGC) well-known text (WKT):

```
COMPD_CS["NAD83(CSRS) / UTM zone 10N + CGVD2013(CGG2013) height",
  PROJCS["NAD83(CSRS) / UTM zone 10N",
    GEOGCS["NAD83(CSRS)",
      DATUM["NAD83_Canadian_Spatial_Reference_System",
        SPHEROID["GRS 1980",6378137,298.257222101,
          AUTHORITY["EPSG","7019"]],
        AUTHORITY["EPSG","6140"]],
      PRIMEM["Greenwich",0,
        AUTHORITY["EPSG","8901"]],
      UNIT["degree",0.0174532925199433,
        AUTHORITY["EPSG","9122"]],
      AUTHORITY["EPSG","4617"]],
    PROJECTION["Transverse_Mercator"],
    PARAMETER["latitude_of_origin",0],
    PARAMETER["central_meridian",-123],
    PARAMETER["scale_factor",0.9996],
    PARAMETER["false_easting",500000],
    PARAMETER["false_northing",0],
    UNIT["metre",1,
      AUTHORITY["EPSG","9001"]],
    AXIS["Easting",EAST],
    AXIS["Northing",NORTH],
    AUTHORITY["EPSG","3157"]],
  VERT_CS["CGVD2013(CGG2013) height",
    VERT_DATUM["Canadian Geodetic Vertical Datum of 2013 (CGG2013)",2005,
      AUTHORITY["EPSG","1127"]],
    UNIT["metre",1,
      AUTHORITY["EPSG","9001"]],
    AXIS["Gravity-related height",UP],
    AUTHORITY["EPSG","6647"]]]
```

Abbreviations

AGL	above ground level (from aircraft at nadir position)
AOI	area of interest
ALS	airborne LiDAR scanning
AGPD	achieved ground point density
AGPS	achieved ground point spacing
ASPRS	American Society for Photogrammetry and Remote Sensing
BCGS	British Columbia Geographic System
CACS	Canadian Active Control System
CBN	Canadian Base Network
CGG2013	Canadian Geoid 2013
CGVD	Canadian Geodetic Vertical Datum
CL	confidence level
CRS	coordinate reference system
CSRS	Canadian Spatial Reference System
DEM	digital elevation model
DQM	data quality measure
DSM	digital surface model
EPSG	European Petroleum Survey Group
FGDC	Federal Geographic Data Committee
FL	flight line
FOV	field of view
FTP	file transfer protocol
GCM	Geodetic Control Marker
GCP	ground control point
GIS	geographic information system
GNSS	global navigation satellite system
GPS	Global Positioning System
IMU	inertial measurement unit
INS	inertial navigation system
LAS	laser file format exchange
LAZ	LASzip
LiDAR	light detection and ranging
LSM	least-squares matching
MASCOT	Management of Survey Control Operations and Tasks
NIR	near infrared
NPD	nominal pulse density
NPS	nominal pulse spacing
NRCan	Natural Resources Canada

NTFS	New Technology File System
OARS	Online Acquisition Reporting System
OGC	Open Geospatial Consortium
PDOP	position dilution of precision
PDRF	Point Data Record Format
PON	Project Operation Number
PPP	Precise Point Positioning
PRF	pulse repetition frequency
QA	quality assurance
QC	quality control
QL	quality level
RGB	red-green-blue
RMSD	root-mean-square difference
RMSDz	vertical (z) root-mean-square difference
$RMSE_r$	horizontal (radial) root-mean-square error
$RMSE_x$	horizontal (x) root-mean-square error
$RMSE_y$	horizontal (y) root-mean-square error
$RMSE_z$	vertical (z) root-mean-square error
RTK	real-time kinematic
SBET	smoothed best estimate trajectory
TB	terabyte
TIN	triangular irregular network
USB	Universal Serial Bus
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
VDOP	vertical dilution of precision
WKT	well-known text

Glossary[6]

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. 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 is equal to or smaller than the reported accuracy value.

- **absolute accuracy** - A measure that accounts for all systematic and random errors in a dataset. Absolute accuracy is stated with respect to a defined datum or reference system.
- **horizontal accuracy** - Positional accuracy of a dataset with respect to a horizontal datum at a specified confidence level or percentile.
- **measurement accuracy** - Closeness of agreement between a test result or measurement result and the true value.
- **positional accuracy** - The accuracy of the position of features, including horizontal and vertical positions, with respect to horizontal and vertical datums.
- **relative accuracy** - A measure of variation in point-to-point accuracy in a dataset. In LiDAR, this term may also specifically mean the positional agreement between points within a swath, adjacent swaths within a lift, adjacent lifts within a project, or between adjacent projects.
- **vertical accuracy** – Positional accuracy of a dataset with respect to a vertical datum at a specified confidence level or percentile.

achieved ground point density (AGPD) – A measure of the calculated net overall point density of classified and georeferenced LiDAR points on the ground (typically last returns) resulting from multiple passes of the LiDAR instrument, within the usable portion of the swath (typically 95%). See also: nominal pulse density

achieved ground point spacing (AGPS) – A measure of the calculated net overall point spacing of classified and georeferenced LiDAR points on the ground (typically last returns) resulting from multiple passes of the LiDAR instrument, within the usable portion of the swath (typically 95%). See also: nominal pulse spacing.

$$AGPS = \frac{1}{\sqrt{AGPD}}$$

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

[6] Some definitions developed from Heidemann [4] and the International Organization for Standardization "Multi-Lingual Glossary of Terms" [13].

altitude – A height measured with respect to the underlying ground surface, meaning above mean sea level.

bare earth - Terrain free from vegetation, buildings, and other built structures. Elevations of the ground.

beam divergence – The beam divergence of a LiDAR system is an angular measure of the spread of an emitted signal pulse with distance from the source. Measured in milliradians (mrad).

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 - (of LiDAR system) – Calibration of a LiDAR system is the process of quantitatively defining the system's responses to known, controlled signal inputs. For LiDAR systems, calibration refers to the process of identifying and correcting for systematic errors in the sensor configuration (alignment), hardware, software and/or procedures. Calibration falls into three main categories:

- **sensor adjustment** - the calibration of a LiDAR system considering straight, and level flight of an aircraft equipped with an IMU and GNSS to determine the accurate position of the sensor in x, y, z with respect to the GNSS and orientation (roll, pitch, yaw) of a LiDAR instrument.
- **lever arm offsets** - Lever arm components are estimated relative to the antenna phase centre and determine the sensor-to-GNSS-antenna offset vectors. These offset vector components are redetermined each time the sensor or aircraft GNSS antenna are moved or repositioned. The components are often field calibrated for each new project to determine corrections to the roll, pitch, yaw, and scale calibration parameters.
- **instrument calibration** - A factory calibration including radiometric and geometric calibration unique to the manufacturer’s hardware and tuned to meet the performance specifications for the model being calibrated. Only assessed and corrected by the instrument manufacturer.

classification - (of LiDAR points) - The classification of LiDAR points in accordance with a classification scheme to identify the type of target from which each LiDAR return is reflected. The process enables differentiation between bare earth terrain points, water, noise, vegetation, buildings, other built features and objects of interest.

confidence level (CL) - 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 - 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 shall never be used as, checkpoints on the same project.

coordinates – A set of three numbers that define a point in 3D space. Traditionally, a vertical coordinate is defined as a 3D coordinate, that is, an x/y-coordinate with an associated z-value.

correction - Compensation for an estimated systematic error.

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.

dilution of precision – uncertainty of coordinates collected with GNSS resulting from the geometric configuration of satellites at the time of measurement

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 ellipsoidal height, and

N is 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. Associated with the highest feature in the landscape like a treetop or top of a building.

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

geospatial data - Information that identifies the geographic location and characteristics of natural or constructed features and boundaries of the earth. This information may be derived from remote sensing, mapping, and surveying technologies.

global navigation satellite system (GNSS) - A constellation of radio-emitting satellites used to determine positions of receivers. The satellites transmit signals that allow a receiver to calculate its location through trilateration.

Global Positioning System (GPS) – A GNSS owned by the United States government.

Globally Unique Identifier (GUID) - A hexadecimal encoded field in the LAS/LAZ file header that allows users to globally relate a dataset to a single project.

ground control point (GCP) - Newly established, on-site survey points used for geometric adjustment of the LiDAR point cloud. These points are defined as non-vegetated points traditionally located in open or urban terrain including bare soil, short grass, asphalt, and concrete surfaces. These are described with markers, paint lines and/or targets.

ground surface points – Refers to LiDAR point data that reach the earth's surface. Not the same as georeferenced, classified ground points.

inertial measurement unit (IMU) - The combination of a 3-axis accelerometer combined with a 3-axis gyroscope. An onboard processor, memory, and temperature sensor may be included to provide a digital interface, unit conversion and to apply a sensor calibration model. The IMU by itself does not provide any kind of navigation solution (position, velocity, attitude), it only actuates as a sensor.

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 (without GNSS input) loses accuracy over time, due to gyroscopic drift.

intensity (LiDAR) - For discrete-return LiDAR instruments, intensity is the recorded amplitude of the energy per area of the reflected LiDAR pulse 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 or the angle of incidence and cannot be considered a true measure of energy. LiDAR intensity data reveal surface textures in the form of grey-scale images. 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 elevation at a location lacking measurement data, where there are measurements surrounding that location. Interpolation is based on the principle of spatial autocorrelation, which assumes that closer points are more similar in elevation than farther points.

laser pulse footprint diameter – the resulting footprint of a single laser pulse on the ground, related to the flying height, and beam divergence of the laser system.

$$d = \gamma H$$

where:

d is the laser pulse footprint diameter (i.e., $\leq$ 0.35 m)

γ is the beam divergence (in radians)

H is the planned flying height

last return - Last received reflected signal that is detected by a 3D imaging system, for a single emitted pulse.

least-squares LiDAR strip adjustment – Adjustment of overlapping LiDAR strips using least-squares matching (LSM), used to detect and correct for geometric errors in the data.

lift – A single takeoff and landing cycle of an aircraft. Often, a single day of acquisition will include multiple lifts. Also referred to as “session” or “flight”.

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, which when combined with position and attitude information from GNSS, INS, and other sensor information within the LiDAR instrument, allows the derivation of the 3D point location of the reflecting target’s location, and other surface qualities.

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

measurement precision - Closeness of agreement between 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 dataset, including formally structured and formatted metadata files.

model – Abstract representation of some aspects of reality.

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

nominal pulse density (NPD) - A common measure of the density of a LiDAR dataset; NPD is the typical or average number of pulses present in a specified areal unit. The NPD is typically expressed as pulses per square metre (pulses/m^2). This value is predicted in mission planning and empirically calculated from the collected data, using only the first or last return points as surrogates for pulses. NPD can be calculated from NPS using the formula:

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

See also: achieved ground point density, nominal pulse spacing.

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 point. This value is predicted in mission planning and empirically calculated from the collected data, using first or last return points as surrogates for pulses. NPS relates to nominal pulse density (NPD) according to the formula:

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

See also: achieved ground point spacing, nominal pulse density.

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

orthometric height – The height, as measured along the plumbline, between the geoid and a point on the Earth's surface, taken positive upwards from the geoid.

pitch - Objects that are free to move in three dimensions, such as an aircraft, can change their attitude by rotating around three orthogonal axes, centred on the vehicle's centre of gravity: the longitudinal, vertical, and lateral axes. Rotation about the lateral axis is called pitch and it is a measure of how far an aircraft's nose is tilted up or down.

platform - Structure which supports a sensor, or sensors.

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.

positioning system – A system of instrumental and computational components for determining position.

precision - Measure of the repeatability of a set of measurements. The closeness with which those measurements agree, although they may all contain a systematic bias resulting in inaccuracy.

primary geodetic reference network – Refers to Canadian Active Control System (CACS) or GNSS occupied on passive Canadian Base Network (CBN) stations.

projected coordinate reference system - A method used to represent the curved, 3D surface of the Earth on a 2D plane.

pulse density – Number of pulses that reach the reflecting surface per square metre, as a function of flying height and pulse repetition frequency.

pulse repetition frequency (PRF) – Rate at which laser emits pulses.

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 data 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 raw data, before and during data acquisition.

quality control (QC) - Set of activities for ensuring quality in products. QC activities focus on identifying defects. Assessing and verifying the quality of the deliverables is part of the QC process.

raster – Array of regular, continuous, tessellating cells representing discrete or continuous data. Each cell contains a single value or multiple values that apply to the entire cell.

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

return (laser pulse) - The reflected signal that is detected by a 3D imaging system, for a given sampling position and a given emitted pulse. For every laser pulse emitted a discrete return sensor can record multiple measurements within the footprint. Additional returns indicate whether a return is single or one of multiple (i.e., first, second, third, et cetera, and last).

roll - Objects that are free to move in three dimensions, such as an aircraft, can change their attitude by rotating around three orthogonal axes, centred on the vehicle's centre of gravity: the longitudinal, vertical, and lateral axes. Rotation about the longitudinal axis is called roll and is a measure of how much the wings of the aircraft are banked.

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

- **$RMSD_z$** the vertical root-mean-square difference in the z direction (elevation):

$$RMSD_z = \sqrt{\sum \frac{\left(Z_i - Z_j\right)^2}{n}}$$

where:

Z_i is the observed elevation value at a location;

Z_j is the observed elevation value at the same location in the comparison dataset, and

n is the total number of locations sampled.

root-mean-square error (RMSE) - The square root of the average of the set of squared differences between dataset coordinate values and coordinate values from an independent source of higher accuracy for identical points. The RMSE is used to estimate the absolute accuracy of both horizontal ($RMSE_x$ and $RMES_y$) and vertical ($RMSE_z$) coordinates where standard or accepted values are known, as with GNSS-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):

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

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 to n.

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

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

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 to n.

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

$$RMSE_r = \sqrt{RMSE_x^2 + RMSE_y^2}$$

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):

$$RMSE_z = \sqrt{\sum \frac{\left(Z_i - Z_i'\right)^2}{n}}$$

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 value checkpoints, and

i is the identification number of each checkpoint from 1 to n.

secondary geodetic reference network - GNSS occupied on an existing provincial survey marker (i.e., brass cap, GCM, etc.), where new coordinates shall be independently produced (i.e., published coordinates of the survey marker are not to be used).

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

supplemental ground control points – Newly established, on-site survey points used as checkpoints in the geometric adjustment of the LiDAR point cloud; no previously existing marker. These points are defined as vegetated (VVA) points traditionally located in all vegetated land cover types including tall weeds and crops, cut blocks and fully forested areas.

swath or **strip** – The extent on the ground of the field of view (FOV) of a laser scan line from a single flight line; a function of scanning angle and flying height AGL.

vendor - 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 network (TIN) – A set of adjacent, non-overlapping triangles computed from irregularly spaced points with x/y coordinates and z-values. The TIN model stores the topological relationship between triangles and their adjacent neighbors. The TIN data structure allows for the efficient generation of surface models for the analysis and display of terrain and other types of surfaces. TINs are able to capture critical points that define terrain discontinuities and are topologically encoded so that adjacency and proximity analyses can be performed.

trilateration - Determining position with respect to two or more other points by measuring the distance between points.

yaw - Objects that are free to move in three dimensions, such as an aircraft, can change their attitude by rotating around three orthogonal axes, centred on the vehicle's centre of gravity: the longitudinal, vertical, and lateral axes. Rotation about the vertical axis is called yaw and is a measure of which direction the nose of the aircraft is pointed with respect to the direction of travel. An aircraft may not fly in the same direction as the nose is pointed if there are significant winds, or other factors, resulting in nonzero yaw values.

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