Figure 1. Map featuring the OLC Middle Fork Willamette River 2015 project data extent.
The Oregon Department of Geology & Mineral Industries (DOGAMI) has contracted with a vendor, Watershed Sciences, Inc. (WSI) to collect high resolution lidar topographic data for multiple areas within the Pacific Northwest. Areas for lidar data collection have been designed as part of a collaborative effort of State, Federal, and Local agencies in order to meet a wide range of project goals. The vendor has agreed to certain conditions of data quality and standards for all lidar data deliverables listed in sections A through C of the 2007-2014 Lidar Data Acquisition Price Agreement (OPA #8865, pages 14-23). Data submitted under this price agreement are to be collected at a resolution of at least 8 pulses per square meter and processed to meet or exceed the agreed upon data quality standards. This document itemizes and reports upon the OLC Middle Fork Willamette River 2015 lidar project (Figure 1) products furnished by the lidar vendor as documentation that all data meets project specific standards.

Upon receipt from vendor, all lidar data for the OLC Middle Fork Willamette River 2015 project was independently reviewed by DOGAMI staff to ensure project specifications were met. All data were inventoried for completeness and checked for quality, which included examining lidar data for errors associated with internal data consistency, model quality, and accuracy. The specific quality control checks are:

- **Data Completeness** examines all data associated with this delivery to ensure that all required data products are present and function correctly. Quality control review is conducted on every data file delivered to DOGAMI. LASer format (LAS) point files have been loaded into TerraSolid™ and ArcGIS™ to ensure complete and correct lidar data coverage and file integrity. Raster and vector files have been viewed in ArcMap and cross referenced with the delivery area to ensure proper coverage, extent and integrity.

- **Spot Diameter Analysis** determines the area of ground that is intersected by a laser pulse from the lidar sensor. The spot diameter is a product of the flying height of the aircraft and the beam divergence of the sensor used during acquisition of the data.

- **Swath-to-Swath Consistency Analysis** involves examining flight line offsets to quantify the accuracy of data calibration. Calibration influences elevation data quality. Poor calibration leads to small but systematic errors within lidar elevation points, which then create inaccuracies within derived lidar elevation models.

- **Visual Analysis** is carried out in order to identify potential data artifacts and misclassifications of lidar point data. Lidar point data is classified as either ground, above ground, or error points. Sophisticated processing scripts are used to classify point data and remove error points. The vendor reviews the automated classification to fix misclassifications of point data. The delivered bare earth digital elevation model (DEM) and highest hit digital surface model (DSM) are then reviewed by DOGAMI to ensure that the data classification is correct and there are no topographic processing artifacts if valid errors are found, data must be corrected and resubmitted.

- **Absolute Accuracy Analysis** compares the delivered bare earth DEMs with independent Ground Check Points (GCPs) to quantify vertical and horizontal accuracy. For each lidar
collection project DOGAMI staff collects independent GCPs with survey-grade GPS, which are then compared against delivered lidar elevation models.

- **Pulse Density Analysis** examines the all-return LAS point cloud and parses out first-return laser points based on the header information for each LAS file. First-return LAS points are then compared to the area of the LAS tile boundaries to determine the pulse density within each LAS tile and the average pulse density for the entire project.

- **Metadata Analysis** compares the structure of the metadata file against FGDC standards. Metadata content is reviewed by using a visual check as well as analysis by the USGS Geospatial Metadata validation service.

**Data Completeness**

The OLC Middle Fork Willamette River 2015 project area was collected between September 14th and September 15th 2015. The total area of delivered data equals 17.48 square miles (11,187 acres). This delivery contains data for the following 8 USGS 7.5’ topographic quarter quadrangles (listed by Ohio Code #) within the boundary of the OLC Middle Fork Willamette River 2015 survey collection area (Figure 2).

**Delivery:** 43122H71, 43122H72, 43122H73, 43122H74, 43122H82, 44122A83, 44122A84, 44123A14
Figure 2. OLC Middle Fork Willamette River 2015 collection area. Data is referenced to USGS 7.5 minute quarter quadrangles within the extents of the OLC Middle Fork Willamette River 2015 project.

We review data acquisition parameters to ensure that the vendor has met all data collection requirements outlined in the Lidar Data Acquisition Price Agreement (OPA #8865). DOGAMI staff verifies acquisition specifications by analyzing LAS point data records. Every LAS file (version 1.2 or higher) contains binary data consisting of a header block, variable length record and point data. The header block contains information such as point numbers, coordinate bounds, and GPS time. The variable length record includes information on who created the data and the recorded length of information. The point data records include information on return number, intensity value and scan angle rank. Using the "Create LAS Dataset" tool in the ArcGIS™ Data Management toolbox, we analyze multiple LAS headers and create statistical information about the collection method for the entire project. Analyzing the LAS files and the information stored within them allows DOGAMI to verify acquisition requirements were met during data collection (Table 1).
<table>
<thead>
<tr>
<th>Specifications</th>
<th>Description</th>
<th>Checked on this delivery</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survey Conditions</td>
<td>Lidar data collection shall be conducted in snow-free conditions with the contractor make best effort to acquire data in leaf-off and low stream conditions</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Pulse Returns</td>
<td>Lidar sensor used must be capable of recording a minimum of 4 returns per laser pulse, including first and last returns.</td>
<td>Yes</td>
<td>5 return classes</td>
</tr>
<tr>
<td>Spot Diameter</td>
<td>Produce an on-ground laser spot diameter no less than 15cm and no greater than 40cm</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Horizontal Datum</td>
<td>North American Datum (NAD) 83 (2011) or the most current horizontal datum at the beginning of the survey</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Vertical Datum</td>
<td>North American Vertical Datum (NAVD) 88 (Geoid 12A) or the most current Geoid model at the beginning of the survey</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Scan Angle</td>
<td>Laser scan angle must not exceed 30 degrees overall (+15 to -15 degrees)</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Swath Overlap</td>
<td>Contractor shall plan surveys with 50% sidelap of adjacent swaths. Survey must be designed for 100% double coverage at planned aircraft height above ground.</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Design Pulse Density</td>
<td>Aggregate design multi-swath pulse density must be 8.0 pulses per square meter or higher.</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Intensity Range</td>
<td>Record intensity range of at least 8 bits</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>GPS Procedures</td>
<td>At least two dual frequency L1-L2 GPS reference receivers operating during missions at 1 Hz or higher. All GPS measurements must be made with Positional Dilution of Precision (PDOP) less than or equal to 3.0 with at least 6 satellites in view.</td>
<td>Yes</td>
<td>None</td>
</tr>
</tbody>
</table>

Table 1. Acquisition Specifications Checklist

We review each product deliverable’s format, resolution and tiling scheme in order to verify content completeness. The OLC Middle Fork Willamette River 2015 lidar project includes data in the format of LAS point files, bare earth grids, highest hit grids, intensity images, trajectory files, ground point density rasters, RTK survey data, a shapefile of the delivery area and the report of survey. Lidar all-return point cloud data is delivered as LAS binary format with all required attribute fields populated (Table 2). DEMs are created from identified ground points and interpolated via triangulated irregular network into an ArcGIS™ Grid format with 3ft cell size (Table 3). DSMs are created from a raster of first-return points that are delivered in ArcGIS™ Grid format with 3ft cell size (Table 4). Georeferenced intensity images created from first-return points and are supplied in TIF format (Table 5). Supplementary data including trajectory files, ground density rasters, real time kinematic ground survey data (used for absolute vertical adjustment) and delivery area shapefiles are provided in various formats (Table 6). The report of survey is a digital text report, supplied by the vendor, that describes lidar data collection methods and processing. The report also provides accuracies associated with calibration, consistency, absolute error and point classification (Table 7).
<table>
<thead>
<tr>
<th>Specifications</th>
<th>Description</th>
<th>Checked on this delivery</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAS File Description</td>
<td>Binary file of all lidar points collected in survey (Class, flight line #, GPS Time, Echo, Easting, Northing, Elevation, Intensity, Scan Angle, Echo Number, and Scanner).</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Format</td>
<td>LAS version 1.2 or most commonly distributed LAS format files, as specified in a Purchase Order</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Projection</td>
<td>Oregon Statewide Lambert Conformal Conic</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Horizontal Datum</td>
<td>NAD 1983 (2011)</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Horizontal Units</td>
<td>International Feet</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Vertical Datum</td>
<td>NAVD 88 (Geoid 12A)</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Vertical Units</td>
<td>International Feet</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Classification</td>
<td>Class 1 - Unclassified; Class 2 - Ground Classification of ground returns must be as complete as is feasible and without avoidable return misclassification</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Return Number</td>
<td>Must list all valid returns – Lidar sensor used must be capable of recording a minimum of 4 returns per laser pulse, including first and last returns.</td>
<td>Yes</td>
<td>Up to 5 returns were recorded</td>
</tr>
<tr>
<td>Time</td>
<td>GPS Seconds per week Use header information – time should be between 0 and 604800</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Attributes</td>
<td>No duplicate entries</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Location</td>
<td>Each return contain easting, northing, elevation information reported to nearest 0.01 meter (0.01 feet)</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>RGB values</td>
<td>All LAS files have RGB values attributed to them where applicable.</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Delivery</td>
<td>LAS data must be delivered in 1/100th USGS 7.5 minute quadrangle tiles or specified in Purchase Order</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Gaps</td>
<td>Check for Gaps in LAS coverage. (Already part of QC process)</td>
<td>Yes</td>
<td>None</td>
</tr>
</tbody>
</table>

Table 2. Quality Control for LAS Deliverables
### Quality Control for Delivered Bare Earth DEMs

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Description</th>
<th>Checked on this delivery</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare Earth DEM</td>
<td>Raster of ground surface, interpolated via triangulated irregular network from identified ground points.</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Description</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Projection</td>
<td>Oregon Statewide Lambert Conformal Conic</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Horizontal Datum</td>
<td>NAD 83 (2011)</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Horizontal Units</td>
<td>International Feet</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Vertical Datum</td>
<td>NAVD 88 (Geoid 12A)</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Vertical Units</td>
<td>International Feet</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Format</td>
<td>Esri™ 32 bit pixel depth floating point grid</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Cell Size / Resolution</td>
<td>3 foot (1m if UTM projection specified)</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Tiling</td>
<td>Full USGS 7.5-minute quadrangle (7.5 minute by 7.5 minute) tiles, unless otherwise specified in a purchase order</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Attributes</td>
<td>No duplicate entries</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Gaps</td>
<td>Surface Models must not have tiling artifacts or gaps at tile boundaries or artifacts such as pits, birds, striping or aliasing</td>
<td>Yes</td>
<td>None</td>
</tr>
</tbody>
</table>

**Table 3. Quality Control for Bare Earth DEMs**

### Quality Control for Delivered Highest-Hit DSMs

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Description</th>
<th>Checked on this delivery</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highest Hit</td>
<td>Tin interpolated grids created from the highest lidar elevation for a given 3ft cell.</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Description</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Projection</td>
<td>Oregon Statewide Lambert Conformal Conic</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Horizontal Datum</td>
<td>NAD 83 (2011)</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Horizontal Units</td>
<td>International Feet</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Vertical Datum</td>
<td>NAVD 88 (Geoid 12A)</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Vertical Units</td>
<td>International Feet</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Format</td>
<td>Esri™ 32 bit pixel depth floating point grid</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Cell Size / Resolution</td>
<td>3 foot (1m if UTM projection specified)</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Tiling</td>
<td>Full USGS 7.5-minute quadrangle (7.5 minute by 7.5 minute) tiles, unless otherwise specified in a purchase order</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Attributes</td>
<td>No duplicate entries</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>------------</td>
<td>----------------------</td>
<td>-----</td>
<td>------</td>
</tr>
<tr>
<td>Gaps</td>
<td>Surface Models must not have tiling artifacts or gaps at tile boundaries or artifacts such as pits, birds, striping or aliasing</td>
<td>Yes</td>
<td>None</td>
</tr>
</tbody>
</table>

**Table 4. Quality Control for Highest-Hit DSMs**

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Description</th>
<th>Checked on this delivery</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity Description</td>
<td>TIFF Raster built using returned lidar pulse intensity values gathered from highest hit returns</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Horizontal Datum</td>
<td>NAD83 2011</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Projection</td>
<td>Oregon Statewide Lambert Conformal Conic</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Horizontal Units</td>
<td>International Feet</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Format</td>
<td>GEOTIFF</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Pixel Depth</td>
<td>8 bit pixel depth gray scale</td>
<td>Yes</td>
<td>16 bit pixel depth – better than required</td>
</tr>
<tr>
<td>Cell Size (X, Y)</td>
<td>1.5 foot (1m if UTM projection specified)</td>
<td>Yes</td>
<td>none</td>
</tr>
<tr>
<td>Normalized</td>
<td>Intensity shall have been normalized if the sensor or combination of sensors used on the project allow.</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Attributes</td>
<td>Intensity file structure conforms to full USGS 7.5 minute quadrangle (7.5 minute by 7.5 minute) tiles</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Gaps</td>
<td>Deliverable tiles checked for significant gaps not covered by aerial acquisition checks and/or caused by processing</td>
<td>Yes</td>
<td>None</td>
</tr>
</tbody>
</table>

**Table 5. Quality Control of Intensity Images**

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Description</th>
<th>Format</th>
<th>Tiling</th>
<th>Projection</th>
<th>Checked on this delivery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Survey Point Shapefile</td>
<td>Ground Control Points used for survey calibration and assessment of absolute vertical accuracy</td>
<td>Esri™ Shapefile</td>
<td>NAD 1983 UTM Zone 10N (2011), meter</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Trajectory Files</td>
<td>Point location measurements of the aircraft used to collect lidar data. Data is collected using an Inertial Measurement Unit (IMU), and collects measurements of: Easting (meters), Northing (meters), Ellipsoid Height (meters) of aircraft, aircraft roll (degrees), aircraft pitch (degrees), aircraft heading (degrees). Measurements are collected at one second intervals.</td>
<td>ascii point file - (TXY2RPH)</td>
<td>Date and time of acquisition</td>
<td>NAD 1983 UTM Zone 10N (2011), meter</td>
<td>Yes</td>
</tr>
<tr>
<td>Trajectory Shapefile</td>
<td>Trajectory data in Esri™ Shapefile format attributed with project name and date of acquisition for each flight line</td>
<td>Esri™ Shapefile</td>
<td></td>
<td>NAD 1983 UTM Zone 10N (2011), meter</td>
<td>Yes</td>
</tr>
<tr>
<td>7.5 minute Quadrangle</td>
<td>Geometry file depicting the geospatial area associated with deliverables.</td>
<td>Esri™ Shapefile</td>
<td>Full USGS 7.5 minute quadrangle</td>
<td>NAD 1983 Oregon Statewide Lambert Conformal Conic (2011), Intl. Feet</td>
<td>Yes</td>
</tr>
<tr>
<td>0.75 minute 1/100th Quadrangle</td>
<td>Geometry file depicting the geospatial area associated with deliverables.</td>
<td>Esri™ Shapefile</td>
<td>1/100th USGS 7.5 minute quadrangle</td>
<td>NAD 1983 Oregon Statewide Lambert Conformal Conic (2011), Intl. Feet</td>
<td>Yes</td>
</tr>
<tr>
<td>TerraSolid Processing Bins</td>
<td>DGN file that contains processing bins for all LAS files</td>
<td>DXF or DGN file</td>
<td>1/100th USGS 7.5 minute quadrangle</td>
<td>NAD 1983 Oregon Statewide Lambert Conformal Conic (2011), Intl. Feet</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 6. Quality Control for Supplementary Data

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Description</th>
<th>Checked on this delivery</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Overview</td>
<td>Acquisition information that includes location map, project area, total area flown, acquisition dates and specified coordinate system and datum</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Aerial Acquisition</td>
<td>Acquisition parameters including information about the aircraft, sensor, flight elevation and a map of flight line trajectories showing dates of collection</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Report of Ground Survey</td>
<td>A detailed description of GPS procedures used in establishing the reference network and control points for the project. Includes a reference map and table</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
<td>Requirement</td>
<td>Notes</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>-------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>Calibration Report</td>
<td>A report for the systems used in the data acquisition</td>
<td>Yes</td>
<td>More information needed</td>
</tr>
<tr>
<td>Relative Accuracy Assessment</td>
<td>Relative accuracy refers to the internal consistency of the data set and is measured as the differential between lidar points collected from different flight lines. Data should be presented as summary statistics and histogram form based on the entire study area.</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Vertical Accuracy Assessment</td>
<td>Vertical accuracy shall be reported to meet the guidelines of the National Standard for Spatial Data Accuracy (Federal Geographic Data Committee (FGDC), 1998) and ASPRS Guidelines for Vertical Accuracy Reporting for Lidar Data V1.0 (American Society for Photogrammetry and Remote Sensing (ASPRS), 2004). Data shall be presented as both summary statistics and in histogram form.</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Pulse Density Assessment</td>
<td>Contractor’s assessment of pulse density over the project area, including maps showing design pulse density and ground return densities by quarter-quadrangle and histograms of both density parameters.</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Summary Table</td>
<td>Table of deliverables, listing file formats and total number and data volume of each deliverable.</td>
<td>Yes</td>
<td>Table of deliverables not listed</td>
</tr>
</tbody>
</table>

**Table 7. Quality Control of the Report of Survey**
Spot Diameter Analysis

Horizontal accuracy is not specified in the price agreement since true horizontal accuracy is regarded as a product of the lidar spot diameter (SD). The lidar spot diameter is the area of ground that is intersected by a single pulse from the lidar sensor. SD is a function of range and beam divergence. The range is calculated as the distance between the laser aperture and the detected surface. The reported range value is given as above ground level flying height (AGL) of the sensor during collection. Beam divergence ($\gamma$) is the degree by which the light pulse emitted from the sensor fans out from a straight line. Beam divergence is measured in radians, with 1 radian = 57.3 degrees. The lidar SD is calculated by multiplying AGL and beam divergence, $SD = AGL \times \gamma$

OLC Middle Fork Willamette River 2015 data was collected using a Leica ALS80 and Riegl VQ-820G lidar sensors, both flown at 400 meters AGL. The Leica ALS80 specification sheet reports a beam divergence value of 0.20 milliradians to 0.26 milliradians @ 1/e², meaning that ~85% of the laser energy falls within this divergence. This equals an average spot diameter of 0.34 meters. The Riegl VQ-820 G specification sheet reports a beam divergence value of 1 milliradians @ 1/e². This equals an average spot diameter of 0.6 meters. The range of spot diameters for the OLC Middle Fork Willamette River 2015 project is between 0.34 meters and 0.60 meters. This equals an average spot diameter of 0.47 meters for these deliveries.

Swath-to-Swath Consistency Analysis

DOGAMI has specified that lidar consistency must average less than 0.15m (0.49 feet) in vertical offsets between flight lines. DOGAMI measures consistency offsets throughout delivered datasets to ensure that project specifications are met.

Consistency refers to lidar elevation differences between overlapping flight lines. Consistency errors are created by poor lidar system calibration settings associated with sensor platform mounting. Errors in consistency manifest as vertical offsets between individual flight lines. Consistency offsets were measured using the "Find Match" tool within the TerraMatch© software toolset. This tool uses aircraft trajectory information linked to the lidar point cloud to quantify flight line-to-flight line offsets.

To quantify the magnitude of this error, 70 of 70 delivered data tiles (100%) were examined for vertical offset between flight lines. All tiles had more than 1000 points, our minimum required for analysis. Each tile measured 750 x 750 meters in size (Figure 4). The average number of points used for flight line comparison was 76,088,886 per tile (Table 8a). Error measurements were calculated by differencing the nearest point from an adjacent flight line within 1 meter in the horizontal plane and 0.2 meters in the vertical plane. Each flight line was compared to adjacent flight lines, and the average magnitude of vertical error was calculated. 86 flight lines out of 86 total flight lines (100%) were sampled and compared for consistency.
Results of the consistency analysis found the average flight line offset to be 0.03 meters (0.09 feet) with a maximum error of 0.06 meters (0.19 feet) (Table 8b). Distribution of error showed 98% of all error was less than 0.06 meters (0.19 feet) and 100% less than 0.07m (0.22 feet) (Figure 4 and 5). These results show that all data are within specification.
Figure 3. Spatial distribution of flight lines and processing tiles used in the consistency analysis.
Table 8a. Summary Results of Consistency Analysis

<table>
<thead>
<tr>
<th>Summary Statistics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td># of Tiles</td>
<td>70</td>
</tr>
<tr>
<td># of Flight Line Sections</td>
<td>86</td>
</tr>
<tr>
<td>Avg. # of Points</td>
<td>76,088,866</td>
</tr>
<tr>
<td>Avg. Magnitude Z error</td>
<td>0.03 meters</td>
</tr>
</tbody>
</table>

Table 8b. Descriptive Statistics for Magnitude Z Error.

<table>
<thead>
<tr>
<th>Descriptive Statistics</th>
<th>Meters</th>
<th>Feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.03</td>
<td>0.09</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Sample Variance</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Range</td>
<td>0.04</td>
<td>0.13</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.06</td>
<td>0.19</td>
</tr>
<tr>
<td>Maximum Absolute vertical offset</td>
<td>0.15</td>
<td>0.49</td>
</tr>
</tbody>
</table>
Figure 4. Flight line Consistency Histogram in meters
Figure 5. Flight line Consistency Histogram in feet

Visual Analysis

Lidar 3ft grids were loaded into ArcGIS™ software for visual analysis. Data were examined through slope and hillshade models of bare-earth returns. Hillshades of the highest hit models were used to identify areas of missing ground (Figure 6). Both bare-earth and highest hit rasters were examined for calibration offsets, tiling artifacts (Figure 7), seam line offsets, pits (Figure 8), and birds.

Calibration offsets typically are visualized as a corduroy-like pattern within a hillshaded lidar model. These offsets present themselves along steep slopes and typically stand out more in highest hit models than bare earth. Tiling artifacts are a result of missing or misclassified data along the edge of lidar processing tiles. These artifacts present themselves as linear features typically 1-2 grid cells in width, and are present in both the highest hit and bare earth models (Figure 7). Seam line offsets occur where two distinct days of lidar data overlap. Errors occur as a result of improper absolute vertical error adjustments. These errors are typically visualized as a linear stair step
running along the edge of connecting flight lines. Pits and birds refer to uncommonly high or low points that are the result of atmospheric and sensor noise. Pits (low points) typically occur where the laser comes in contact with water on the ground (Figure 8). Birds (high points) typically occur where the laser comes into contact with atmospherics\(^1\).

During visual analysis of OLC Middle Fork Willamette River 2015 raster data, 10 observed errors were digitized for spatial reference and stored in Esri\(^*\) shapefile format. Each feature was assigned an ID value and included a brief description of the observed error. The shapefile was then delivered to the vendor for locating and fixing errors. Upon receiving the observed error locations, the vendor performed an analysis to conclude whether the error was valid and provided comments on how the data was adjusted. None of the 10 observed errors (0\%) were adjusted. Some of the reported errors by DOGAMI staff were not fixed by the vendor because either there was not enough data to improve the DEM or the QC call was not valid (call to remove bridge points from ground when the feature was actually a culvert). Errors that were not fixed by the vendor were reviewed by DOGAMI staff to ensure justification was valid. Final sets of lidar 3 ft grids were loaded into ArcGIS\(^*\) software and examined to ensure edits were made and visually inspected an additional time for completeness (Figure 9).

\(^1\)Atmospherics include clouds, rain, fog, or virga

**Figure 6. Example of missing ground in lidar bare earth data.** Ground is clearly visible in highest hit model, but has been removed from the bare earth model. This type of classification error is common near water body features.
Figure 7. Example of tile artifact found in highest hit lidar data. Artifact is a seam line error created due to misclassification of ground at edge of lidar processing tiles.
Figure 8. Example of "Pit" caused by low point in ground model. Pits are caused when standing water absorbs the lidar pulse. Pits are evident in ground model as the lowest point elevation is assigned to the grid cell value. Inversely the pit is not observable in the highest hit model as the highest point elevation is assigned to the grid value.
Figure 9. Spatial distribution of visual QC errors located by DOGAMI staff.
Absolute Accuracy Analysis

Absolute accuracy refers to the mean vertical offset of lidar data relative to measured ground-control points (GCP) obtained throughout the lidar sampling area. DOGAMI used two Trimble™ R10 GNSS Systems, and an optional Trimmark™ 3 radio (Figure 10) to measure GCPs for OLC Middle Fork Willamette River 2015 project. One Trimble™ R10 GNSS System was mounted on a fixed height (typically 1.8 m) tripod and located over a known geodetic survey monument followed by a site calibration on several adjacent benchmarks to precisely establish a local coordinate system. The second R10 GNSS System, referred to as the "rover" unit is then attached to a fixed height survey pole for static point measurements within the project boundaries. In areas of flat terrain and limited tree cover, the rover unit will use a truck mount on the side of a vehicle to collect continuous RTK points along hard surfaces. Utilizing both single point and continuous RTK collection allows for GCP collection in various terrain and topography as well as provide a density of GCPs on hard surfaces for accurate reporting of absolute accuracy. The Trimmark™ 3 radio is used in areas of high relief in order to extend the range of the R10 internal radio broadcast. The Trimble™ R10 GNSS Systems typically have a broadcast range of 3 miles without the Trimmark™ 3 radio.

![Image](image_url)

*Figure 10. The Trimble R10 base station antenna located over a known reference point outside Baker City. Corrected GPS position and elevation information is then transmitted either by Internal Radio or by a Trimmark III base radio to the R10 GPS rover unit.*

The approach adopted for DOGAMI lidar surveys was comprised of four components:
1) Verify the horizontal and vertical coordinates established by Watershed Sciences for a select number of survey monuments used to calibrate the lidar survey. These surveys typically involved a minimum of two hours of GPS occupation over a known point. The collected ephemeris data is then submitted to the National Geodetic Survey (NGS) Online Positioning User Service (OPUS) for post-processing against several Continuously Operating Reference Stations (CORS) operated by the NGS.

2) Collect GCPs in vegetative and non-vegetative land cover within the project area. Vegetative land cover GCP collection is typically achieved through static point collection. Non-vegetative point collection is typically achieved through continuous RTK collection along relatively flat surfaces (roads, paths, parking lots etc.).

3) Post-process collected GCP points in Trimble Business Center. GCPs collected in the field are filtered to remove points that have horizontal and vertical precisions less than 0.03m. GCP points that have a high Point Dilution of Precision (PDOP) are also removed since high PDOP values affect horizontal and vertical precision. GCPs that have been filtered for accuracy are then exported out to TBC.

4) GCPs elevation values are compared to the lidar derived DEM raster elevations. Statistical information on the offsets between GCPs and the DEM rasters is calculated and analyzed by DOGAMI staff.

After collecting the GCP data in the field, the GPS data was post-processed using Trimble Business Center software. Data post-processing typically involved calibrations against at least three CORS stations as well as from local site calibrations performed in the field using those benchmarks that had been independently verified. This step is critical in order to eliminate various survey errors. For example, Trimble reports that the R10 GNSS System have horizontal errors of approximately ±1-cm + 1ppm (parts per million * the baseline length) and ±2-cm in the vertical (Trimble Navigation System, 2005). These errors may be compounded by other factors such as poor satellite geometry, multipath, and poor atmospheric conditions, combining to increase the total error to several centimeters. Thus, the site calibration process is critical in order to minimize these uncertainties. Data is post processed to refine measurements so that horizontal and vertical errors are less than 0.03 meters (0.065 feet). GCPs with Point Dilution of Precision (PDOP) values higher than 3.0 are not used for comparison. High PDOP values reduce the horizontal and vertical precision of collected GCPs, which is why we filter for high PDOP values.

DOGAMI collected GCP points on October 27, 2016. Ground conditions were good on the day of collection with no snow and no inclement weather. The base stations used in the GCP data collection for OLC Middle Fork Willamette River 2015 were located on monument Lane_13 which was established by the vendor (See Report of Survey). Accuracy assessments of survey monuments are provided in the form of an OPUS solution from NGS, below is the OPUS solution for monument Lane_13.

<table>
<thead>
<tr>
<th>NAV FILE</th>
<th>OBS USED</th>
<th>OBS USED</th>
</tr>
</thead>
<tbody>
<tr>
<td>brdc3010.16n</td>
<td>6777 / 7110</td>
<td>95%</td>
</tr>
<tr>
<td>ANT NAME: TRMR10</td>
<td>QUALITY IND.</td>
<td>30.78/42.97</td>
</tr>
<tr>
<td>NONE</td>
<td>NORMALIZED RMS</td>
<td>0.365</td>
</tr>
<tr>
<td>ARP HEIGHT: 2.34564698867265</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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X: -2501835.031(m) 0.009(m) -2501835.916(m) 0.009(m)
Y: -3853817.909(m) 0.017(m) -3853816.678(m) 0.017(m)
Z: 4409086.121(m) 0.020(m) 4409086.134(m) 0.020(m)

LAT: 44 0 41.088452 0.004(m) 44 0 41.09722 0.004(m)
E LON: 237 0 32.51358 0.004(m) 237 0 32.45016 0.004(m)
W LON: 122 59 27.48642 0.004(m) 122 59 27.54984 0.004(m)
EL HGT: 118.644(m) 0.027(m) 118.257(m) 0.027(m)
ORTHO HGT: 142.085(m) 0.031(m) [NAVD88 (Computed using GEOID12B)]

UTM COORDINATES STATE PLANE COORDINATES
UTM (Zone 10) SPC (3602 OR S)
Northing (Y) [meters] 4873140.428 263442.226
Easting (X) [meters] 500723.958 1300276.072
Convergence [degrees] 0.00627513 -1.70418949
Point Scale 0.99960001 1.00000292
Combined Factor 0.99958141 0.99998432

DOGAMI was able to test the horizontal accuracy of survey monuments used to reference the lidar data while conducting vertical control measurements. For internal purposes only, the XY coordinates of survey monuments surveyed by DOGAMI were compared to the survey monuments provided by the vendor. The average horizontal accuracy for all monument locations occupied by DOGAMI during GCP data collection is 0.004 meters Northing and 0.004 meters Easting (Table 9). The average root mean square error (RMSE) for positional accuracy for all monument locations occupied by DOGAMI during GCP data collection is 0.365 meters.

<table>
<thead>
<tr>
<th>Occupied Monuments</th>
<th>meters</th>
<th>feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. Northing accuracy</td>
<td>0.004</td>
<td>0.013</td>
</tr>
<tr>
<td>Avg. Easting accuracy</td>
<td>0.004</td>
<td>0.013</td>
</tr>
<tr>
<td>Avg. RMSE for positional accuracy</td>
<td>0.365</td>
<td>1.197</td>
</tr>
</tbody>
</table>

Table 9. Average accuracy values for occupied monuments

Vertical accuracy analysis of delivered lidar data consisted of differencing collected GCP data and the lidar Digital Elevation Models (DEM) to expose offsets. These offsets were used to produce a mean vertical error and vertical RMSE value for the entire delivered data set. Project specifications list the maximum acceptable mean vertical offset to be 0.20 meters (0.65 feet) and the maximum vertical RMSE to not exceed 0.0925 meters (0.303 feet).

A total of 25 measured GCPs were obtained in the OLC Middle Fork Willamette River 2015 project area and were compared with the lidar elevation grids (Figure 12). The data delivered to DOGAMI was found to have a mean vertical offset of 0.07 meters (0.22 feet) and an RMSE value of 0.08 meters...
Offset values ranged from -0.18 meters (-0.59 feet) to 0.002 meters (0.006 feet) (Table 10 and Figure 13 and 14).
Figure 11. Locations of GCPs surveyed by DOGAMI staff. Data was used to test absolute accuracy for the OLC Middle Fork Willamette River 2015 project areas.
Table 10. Descriptive Statistics for absolute value vertical offsets.

<table>
<thead>
<tr>
<th>Descriptive Statistics</th>
<th>Meters</th>
<th>Feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.070</td>
<td>0.220</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.008</td>
<td>0.026</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.043</td>
<td>0.141</td>
</tr>
<tr>
<td>Range</td>
<td>0.192</td>
<td>0.629</td>
</tr>
<tr>
<td>Minimum</td>
<td>-0.180</td>
<td>-0.590</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.002</td>
<td>0.006</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.080</td>
<td>0.260</td>
</tr>
<tr>
<td>Maximum Absolute Mean Offset</td>
<td>0.20</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Histogram Showing Range of Elevation Difference Between Middle Fork Willamette River 2015 Lidar DEM and GPS Measurements, n = 25

Figure 12. Histogram of absolute vertical accuracy in meters.
Pulse Density

DOGAMI has specified that the aggregate design multi-swath pulse density for the OLC Middle Fork Willamette River 2015 project must be 8.0 pulses per square meter (m²) or higher. Pulse density is calculated as the number of pulses per unit area, commonly measured as pulses per m². This calculation is based on the number of first return pulses divided by the area of the tile.

The all-return LAS points are comprised of multiple returns from each laser pulse. These multiple returns are created when a laser pulse encounters multiple reflection surfaces as it travels toward the ground. Pulse density was measured by parsing out first-return points from the all-return LAS files. First-return points are used to assess pulse density because multiple returns from a single pulse would introduce bias into the statistics. DOGAMI staff used Bentley© Microstation software to filter the LAS point files and output new LAS files that only contain first-return points. Statistics were calculated on the newly created files using the ArcGIS 3D analyst tool called “Point File Information.” This tool calculated the total number of first return points for each LAS file. Each Las file’s first return point count was then compared to the size of each LAS file to determine the overall pulse per square meter. Using the 1/100th USGS 7.5 minute quadrangle extents, DOGAMI staff created polygons that graphically depict the pulse density of the project area (Figure 14).

To quantify pulse density of OLC Middle Fork Willamette River 2015, 70 all-return LAS files (100%) were parsed into first-return point files and compared to their data extents. Results of the pulse density analysis found the average pulse density to be 79.9 pulses per m² (Table 11). Certain types of surfaces (dense vegetation, water) may return fewer pulses than the laser originally emitted;
therefore density values can vary according to terrain and land cover. Pulse densities for OLC Middle Fork Willamette River 2015 LAS tiles ranged from 49.7 pulses per m² to 136.8 pulses per m² (Figure 14). 70 LAS tiles out of 70 (100%) have a pulse density of ≥ 8.00 pulses per m² (Figure 15). These results show that all data are within tolerances of pulse density according to the contract agreement.

<table>
<thead>
<tr>
<th>Summary Statistics</th>
<th>Pulses per m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>79.9</td>
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<tr>
<td>Standard Error</td>
<td>2.20</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>18.4</td>
</tr>
<tr>
<td>Sample Variance</td>
<td>339.5</td>
</tr>
<tr>
<td>Range</td>
<td>87.1</td>
</tr>
<tr>
<td>Minimum</td>
<td>49.7</td>
</tr>
<tr>
<td>Maximum</td>
<td>136.8</td>
</tr>
<tr>
<td>Required mean pulse density</td>
<td>≥ 8</td>
</tr>
</tbody>
</table>

Table 11. Summary Results of Pulse Density Analysis
Figure 14. Pulse Density of 1/100th USGS 7.5 minute quarter quadrangle LAS tiles.
Metadata Analysis

Metadata analysis compared the structure of the metadata file against FGDC standards. All or a portion of the Metadata content was reviewed by using a visual check in Esri™ ArcCatalog as well as analysis by the USGS Geospatial Metadata validation service: [http://geonnsdi.er.usgs.gov/validation/](http://geonnsdi.er.usgs.gov/validation/). No structure issues were found when validating the compliance of metadata to FGDC standards.
Acceptance

The data described in this report meet and exceed project specifications laid out in the contracted data standards agreement. All components of data to be delivered have been received as of March 29, 2017. Quality control has confirmed that all delivered data is within specification and function correctly. Quality Control has evaluated acquisition parameters to confirm that data was collected within project design scope. Consistency analysis has concluded that all data contains flight line to flight line vertical offset less than the threshold of 0.15 meters as specified in the agreement. The vendor has adequately responded to all fixable errors identified as part of the visual analysis. Perceived grid errors identified by DOGAMI that were found to be false have been documented by the vendor and explained to the satisfaction of DOGAMI reviewers. Absolute accuracy analysis of the data has concluded that absolute vertical error of lidar data is less than the specified tolerance of 0.20 meters as specified in the data standards agreement. Pulse density has been analyzed through the project area and the aggregate pulse density is greater than 8.0 pulse per square meter.

Approval Signatures

[Signature]
Date: 7/16/18

Jacob Edwards
Lidar Database Coordinator – Department of Geology & Mineral Industries