Introduction to LiDAR Technology and Applications in Forest Management

Presented by Rory Tooke, Douglas Bolton and Nicholas Coops
Integrated Remote Sensing Studio
Faculty of Forestry
University of British Columbia. Canada
What is LiDAR?

- LiDAR = Light Detection And Ranging
- Active form of remote sensing
- Measures the distance to target surfaces using narrow beams of near-infrared light (e.g. 1064 nm).
- Primarily operated on airborne platforms for forestry applications
  - However, spaceborne (GLAS) and field based LiDAR instruments have also been developed.
LiDAR is Distance Measurement

$R =$ Range or distance
$c =$ Speed of light (299 792 km / sec)
$tp =$ Time the pulse is emitted from the sensor
$t =$ Time the pulse arrives back at the sensor

Divided by 2 to compensate for the round-trip distance
LIDAR systems incorporate three technologies:

(i) laser ranging for accurate distance measurement,

(ii) satellite positioning using the Global Positioning System (GPS) to determine the geographic position and the height of the sensor, and

(iii) aircraft attitude measurement using an inertial measurement unit (IMU) to record the precise orientation of the sensor.
LIDAR from Space (Theoretical)

Images and movies from NASA and used with permission
Point Registration

- The coordinates \((x, y, z)\) of target objects are determined by:
  1. Differential GPS (DGPS)
     - Determine precise location of the LiDAR instrument
  2. Inertial Measurement Unit (IMU)
     - Determine the orientation of the LiDAR instrument
  3. LiDAR pulse orientation
  4. Range to target object
     - By recording the time until pulse return
A LiDAR Pulse

A waveform describes the entire return intensity as a function of time for each pulse.
A waveform describes the entire return intensity as a function of time for each pulse.
Storage of the Return Signal

- The returned energy is stored as either:
  - Discrete points
    or
  - Waveform data
Discrete Return Data

- The returned pulse is classified into one or more discrete returns
  - Returns are recorded when the return energy exceeds the systems predefined threshold
  - Early LiDAR systems were designed to record only the distance to the first target
  - Later systems recorded multiple returns
  - Last returns are particularly important for detecting the ground surface
Discrete Return Data

- Cross-section of discrete return data

![Graph showing elevation against easting with forest canopy and ground markers]
Waveform Data

- Waveform data is less common than discrete return data
  - As technology advances, it is becoming easier to record the full waveform

- Much larger volume of data

- Methods of processing waveform data are not as advanced
LiDAR Technology

• Advantages of LiDAR technology:
  – Assessment of vertical structure of forests at high spatial resolutions
  – Accurate estimates of surface height
  – Can operate independently of sunlight

• Growing interest in LiDAR in past two decades:
  – In the beginning, primary interest was the development of digital elevation models (DEM)
    • Looking past the vegetation
  – In the past decade, the potential for LiDAR in forestry applications has been realized
    • Measure tree heights to sub-metre levels of accuracy
    • Estimate forest attributes such as stem volume and basal area
Different Types of LiDAR instruments

- Profiling LiDAR
- Small-footprint LiDAR
- Large-footprint LiDAR
- Ground based LiDAR
Profiling LiDAR

- Early airborne LiDAR instruments

- Measure height information along single transects with a fixed nadir view angle

- Advantages:
  - Relatively inexpensive technology
  - Great sampling tool

- Limitation:
  - Lack of spatial detail
LiDAR Scanning Pattern

- More advanced scanning systems were later developed (~1990s onwards).
  - Rotating mirror used to direct pulses perpendicular to flight direction
- Both small- and large-footprint LiDAR use this approach
Small-footprint LiDAR

- Beam diameters at intercepting surface < 1 m
- Typically record high sampling densities (>1 / m²)
- Accuracy ~15 cm vertically and 40 cm horizontally
- Operated on fixed wing or helicopter platforms
- Commercially available
- Sensors now emit up to 260 000 pulses / sec
  - 3 years ago this was closer to 25 000 pulses / sec
- Increase from first / last return combinations to 5 returns per pulse
  - Ability to separate returns by smaller distances (e.g. 2 m intervals)
  - Option to record full waveform is becoming more common
Large-footprint LiDAR

- These instruments use larger beam diameters at intercepting surface (generally 5 to 25 m)
- Signal is averaged across the footprint
  - Record the entire returned signal as a function of time (waveform)
- Currently only experimental (e.g. SLICER and LVIS)
Ground based LiDAR

- Scanner is placed below the forest canopy
- Algorithms are deployed to detect individual tree stems
  - Stems can be occluded by other stems
- Current research aims to make ground based LiDAR an operational inventory tool
Working with Discrete Return LiDAR data

- How do we derive meaningful measurements from a LiDAR point cloud?

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
TERRAIN GENERATION

• LIDAR usually has high spatial sampling (0.1 – 4 m).
• Accuracy of 3-D location very good (<20 cm).
• Post-processing is done to ensure
  – Recommend 2 GPS ground receivers with known positions making absolute georeferencing possible
  – Filtering of data to ascertain ground versus non-ground hits.

• Typical Accuracies: 15 cm in elevation and horizontal position
• Spot spacing much denser for slower aircraft
• More reliable/accurate DTM through denser spot spacing – more data collected
• Highest accuracy heights at nadir and decrease as swath angle increases
Step 1: Extract probable ground returns

- Ground points are often classified by LiDAR vendor

Step 2: Create surface from ground returns

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Creating A Digital Elevation Model (DEM)

- The density of ground points depends on the vegetation structural class
- Fewer pulses will reach the surface under dense canopies
- Methods of interpolation are needed where ground return densities are low

Analysis performed at Pacific Rim National Park, Vancouver Island
Interpolation Methods

- Interpolation is the estimation of values at unsampled locations.
- Algorithms fit a continuous surface through a set of measured points (e.g. LiDAR ground returns)
- Algorithms differ in their ease of use, mathematical complexity, and computational expense.

Sources: Johnston et al. 2001; Maune et al. 2001
Creating A Digital Elevation Model (DEM)
Validating DEM

- Difficult task due to high level of accuracy

- Differential GPS is affected by vegetation cover (Naesset and Jonmeister, 2002).

- DEM accuracy may vary spatially across the landscape due to vegetation cover and ground slope

- Accuracy is generally within 1 m
DEM of Alex Fraser Research Forest
Current uses in operational planning:

- Contour lines
  - Road planning
  - Block boundaries
  - Stream modeling

- Operational slope classes
  - < 35% slope: Conventional ground skidding
  - 35-50% slope: Requires specialized equipment
  - > 50% slope: Consider cable yarding

Uses provided by: Don Skea, AFRF
Visualization for
Malcolm Knapp Research Forest
Visualization for
Malcolm Knapp Research Forest

Lidar visualizations produced with FUSION/LDA software – USDA Forest Service
Derive Heights in Relation to the Surface

Point elevation

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Derive Heights in Relation to the Surface

Point elevation

Surface elevation

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Derive Heights in Relation to the Surface

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
• Two scales of analysis are commonly undertaken
  – Tree scale
    • Individual trees located in the LiDAR data and a range of tree attributes derived (e.g. Maximum tree height, crown area, basal area….)
  – Plot scale
    • Attributes are estimated over a defined area (square, rectangular or circular). For example, maximum plot height, basal area, height percentiles
Tree Level Analysis

**Step 1:** Create Digital Surface Model (DSM)

**Step 2:** Deploy algorithms to identify peaks in DSM

Difficult in dense canopies

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Tree Level Analysis
Tree Level Analysis

Identification of individual trees using a Digital Surface Model

DSM

DSM with trees identified
Tree Level Analysis – Maximum Tree Height

• High levels of accuracy with differences generally < 1 m

• Some argue LiDAR heights are more accurate than field measurements of tree height

• The derivation of tree heights will be affected by:
  
  – Sampling density
    • High density improves changes of hitting tree top
  – Tree dimensions
    • A smaller crown will have fewer returns
  – Occlusion
    • Adjacent trees
Tree Level Analysis – Maximum Tree Height

- Side Height
- Good Height
- Incorrect Height
- Interpolated Surface

Missed tree (no ‘peak’)
Missed good height
Missed good height

Modified based on Zimble et al. 2003
Plot Level Analysis

LiDAR Point Cloud for Alex Fraser Research Forest
Plot Level Analysis

• Summarize LiDAR data on a grid

LiDAR Point Cloud for Alex Fraser Research Forest

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Plot Level Analysis

• Summarize LiDAR data on a grid
• Use summary metrics to estimate forest attributes for each grid cell

LiDAR Point Cloud for Alex Fraser Research Forest

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Plot Level Analysis

• Summarize LiDAR data on a grid

• Use summary metrics to estimate forest attributes for each grid cell

• Must first develop relationships between LiDAR metrics and forest attributes
Plot Level Analysis

- Summarize LiDAR data on a grid
- Use summary metrics to estimate forest attributes for each grid cell
- Must first develop relationships between LiDAR metrics and forest attributes

LiDAR Point Cloud for Alex Fraser Research Forest

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Plot Level Analysis

LiDAR Point Cloud for Alex Fraser Research Forest

- Extract LiDAR data associated with each plot

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Plot Level Analysis

- Extract LiDAR data associated with each plot
- Summarize the LiDAR data within each plot
Plot Level Analysis

- Extract LiDAR data associated with each plot
- Summarize the LiDAR data within each plot
- Develop relationships between the LiDAR metrics and the plot level data

LiDAR Point Cloud for Alex Fraser Research Forest
Plot Level Analysis

LiDAR Point Cloud for Alex Fraser Research Forest

Site 1 – High Volume Example

Site 2 - Low Volume Example

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Plot Level Analysis

- Use first returns to calculate LiDAR metrics
  - Forest attributes calculated with first returns found to be more robust than using all returns (Bater et. al 2011)
Plot Level Analysis

Calculate Cover Metrics

Cover 30 – 40 m

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Plot Level Analysis

Calculate Cover Metrics

Cover 20 – 30 m

High Volume Site

Low Volume Site

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Plot Level Analysis

Calculate Cover Metrics

Cover 10 – 20 m

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Plot Level Analysis

Calculate Cover Metrics

Cover Above 2 m

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Plot Level Analysis

Calculate Height Metrics

Mean Height

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Plot Level Analysis

Calculate Height Metrics

10th Percentile

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Plot Level Analysis

Calculate Height Metrics

20\textsuperscript{th} Percentile

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Plot Level Analysis

Calculate Height Metrics

30th Percentile

Height Metrics

26.5 m

12.5 m

High Volume Site

Low Volume Site

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Plot Level Analysis

Calculate Height Metrics

40th Percentile

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Plot Level Analysis

Calculate Height Metrics

50\textsuperscript{th} Percentile

28.2 m
16.5 m

High Volume Site
Low Volume Site

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Plot Level Analysis

Calculate Height Metrics

60th Percentile

28.8 m

17.5 m

High Volume Site

Low Volume Site

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Plot Level Analysis

Calculate Height Metrics

70th Percentile

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Plot Level Analysis

Calculate Height Metrics

80th Percentile

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Plot Level Analysis

Calculate Height Metrics

90\textsuperscript{th} Percentile

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Plot Level Analysis

Calculate Height Metrics

99th Percentile

High Volume Site

Low Volume Site

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Plot Level Analysis

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Coefficient of Variation

Measure of the structural diversity

Plot Level Analysis

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
Plot Level Analysis

• Once metrics are calculated at the plot level:
  
  – Investigate the relationships between metrics and measured forest attributes
    • Mean tree height, dominant tree height, stem volume, basal area
  
  – Develop statistical models to predict forest attributes using several LiDAR metrics
    • Usually a combination of a height and cover metric
  
  – Statistical models are applied to gridded LiDAR metrics to predict forest attributes across the study area
Deriving Forest Attributes

LiDAR point cloud

Step 1: Calculate gridded metrics

Step 2: Apply statistical model

Stem volume estimation

Mean elevation

Cover above 2m

Coefficient of variation

Height (m)

Stem Volume (m$^3$)

LiDAR visualizations produced with FUSION/LDA software – USDA Forest Service
How do we relate lidar to ground data?

- GPS ground plot location
- Make ground measures
- Statistically relate ground measures to lidar metrics
- Can apply these relationships across all lidar grid cells (25 x 25m)
- Metrics not limited to height
- Inventory: Generalize by polygon (ht in m):

### Mean Tree Height

- $r^2 = 0.89$
- $se = 1.50$
- $f = 183.76$
- $p = 0.0000$
- $y = 3.91 + 0.61x$

### Maximum Tree Height

- $r^2 = 0.81$
- $se = 3.81$
- $f = 93.03$
- $p = 0.0000$
- $y = 0.38+0.96x$

### Variation of Tree Height

- $r^2 = 0.90$
- $se = 0.86$
- $f = 200.78$
- $p = 0.0000$
- $y = 0.1845 + 1.27x$

### Mean Diameter (dbh)

- $r^2 = 0.31$
- $se = 7.85$
- $f = 11.03$
- $p = 0.0028$
- $y = 15.76 + 0.75x$
Example Equation and Results

<table>
<thead>
<tr>
<th>Radius (m)</th>
<th>Plot Size (m²)</th>
<th>Fitted OLS Regression Model</th>
<th>$R^2$</th>
<th>$SEE$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1257</td>
<td>$\hat{Y} = -51.3755 + 13.0245 \times Lh_{0.6} + 3.6330 \times CC_{0.0}$</td>
<td>0.960</td>
<td>38.64</td>
</tr>
</tbody>
</table>

$\hat{Y}$ – TAGB  
$Lh_{0.5}$ – 50th percentile of laser canopy height (m).  
$Lh_{0.6}$ – 60th percentile of laser canopy height (m);  
$CC_{0.0}$ – canopy density (%) at 2 m above the ground surface.  
$R^2$ – multiple coefficient of determination.  
$SEE$ – standard error of the estimate in transformed units.
Example of Multiple Regression Equations at the Plot Scale

**Table 6**

Relationships between logarithmic transformations of ground-based characteristics of the 200 m² sample plots (dependent variables) and laser-derived metrics from stepwise multiple regression analysis

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Predictive model</th>
<th>$R^2$</th>
<th>RMSE</th>
<th>$\kappa$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Young forest (n = 56)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\ln h_L$</td>
<td>$0.46 + 1.149\ln h_{901} - 0.28\ln h_{maxf}$</td>
<td>0.95</td>
<td>0.06</td>
<td>5.0</td>
</tr>
<tr>
<td>$\ln h_{dom}$</td>
<td>$0.568 + 1.169\ln h_{901} - 0.286\ln h_{maxf}$</td>
<td>0.93</td>
<td>0.07</td>
<td>5.0</td>
</tr>
<tr>
<td>$\ln d_g$</td>
<td>$-0.867 + 0.217\ln h_{10t} + 0.665\ln h_{901} - 0.805\ln d_{s01}$</td>
<td>0.78</td>
<td>0.12</td>
<td>3.1</td>
</tr>
<tr>
<td>$\ln N$</td>
<td>$15.99 - 1.182\ln h_{901} + 3.08n d_{s01}$</td>
<td>0.68</td>
<td>0.28</td>
<td>1.8</td>
</tr>
<tr>
<td>$\ln G$</td>
<td>$3.492 + 0.536\ln h_{10t} + 1.388\ln d_{s01}$</td>
<td>0.89</td>
<td>0.14</td>
<td>2.2</td>
</tr>
<tr>
<td>$\ln V$</td>
<td>$3.473 + 1.336\ln h_{mean} + 1.477\ln d_{s01}$</td>
<td>0.93</td>
<td>0.16</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>Mature forest, poor site quality (n = 36)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\ln h_L$</td>
<td>$0.285 + 1.011\ln h_{901} - 0.107\ln h_{901}$</td>
<td>0.86</td>
<td>0.05</td>
<td>2.2</td>
</tr>
<tr>
<td>$\ln h_{dom}$</td>
<td>$-0.0187 + 1.002\ln h_{maxf}$</td>
<td>0.74</td>
<td>0.08</td>
<td>1.0</td>
</tr>
<tr>
<td>$\ln d_g$</td>
<td>$0.206 + 0.77ln h_{901} - 0.312\ln d_{s01}$</td>
<td>0.54</td>
<td>0.12</td>
<td>1.4</td>
</tr>
<tr>
<td>$\ln N$</td>
<td>$11.24 + 1.195\ln h_{901} - 1.662\ln h_{max} + 1.156\ln d_{20t}$</td>
<td>0.65</td>
<td>0.30</td>
<td>1.7</td>
</tr>
<tr>
<td>$\ln G$</td>
<td>$4.253 + 4.304\ln h_{s01} - 4.022\ln h_{60t} + 0.584\ln d_{s01}$</td>
<td>0.69</td>
<td>0.21</td>
<td>8.5</td>
</tr>
<tr>
<td>$\ln V$</td>
<td>$4.951 - 1.278\ln h_{901} + 5.994\ln h_{s01} - 3.8\ln h_{60t} + 0.766\ln d_{s01}$</td>
<td>0.80</td>
<td>0.20</td>
<td>11.7</td>
</tr>
<tr>
<td><strong>Mature forest, good site quality (n = 52)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\ln h_L$</td>
<td>$0.35 + 0.529\ln h_{901} + 0.355\ln h_{maxf}$</td>
<td>0.82</td>
<td>0.07</td>
<td>5.9</td>
</tr>
<tr>
<td>$\ln h_{dom}$</td>
<td>$0.525 + 0.231\ln h_{s01} + 0.637\ln h_{maxf} + 0.084\ln d_{10f}$</td>
<td>0.85</td>
<td>0.07</td>
<td>4.3</td>
</tr>
<tr>
<td>$\ln d_g$</td>
<td>$0.441 + 0.64ln h_{901} - 0.277\ln d_{s01}$</td>
<td>0.39</td>
<td>0.12</td>
<td>1.7</td>
</tr>
<tr>
<td>$\ln N$</td>
<td>$10.33 - 0.487\ln h_{901} - 0.667\ln h_{cv3} + 1.187\ln d_{s01}$</td>
<td>0.50</td>
<td>0.35</td>
<td>1.9</td>
</tr>
<tr>
<td>$\ln G$</td>
<td>$3.608 + 2.629\ln h_{s01} - 2.171\ln h_{maxf} + 1.26n d_{s01}$</td>
<td>0.75</td>
<td>0.21</td>
<td>3.8</td>
</tr>
<tr>
<td>$\ln V$</td>
<td>$3.151 + 3.027\ln h_{s01} - 1.666\ln h_{maxf} + 1.223\ln d_{s01}$</td>
<td>0.80</td>
<td>0.22</td>
<td>3.8</td>
</tr>
</tbody>
</table>

* $h_L$ = Lorey's mean height (m), $h_{dom}$ = dominant height (m), $d_g$ = mean diameter by basal area (cm), $N$ = stem number (ha⁻¹), $G$ = basal area (m² ha⁻¹), $V$ = volume (m³ ha⁻¹).

Source: Næsset 2002
A Canadian Foothills Project

Study Area

- Hinton FMA ~990,000 ha; 385,000 AVI polygons

• Clients, Partners & Collaborators

- West Fraser Mills, Hinton Wood Prods.
- AB Sustainable Resource Development
- CFS, Pacific Forestry Centre
  - Dr. Mike Wulder, Dr. Gordon Frazer,
    Joanne White, Geordie Hobart
- University of BC
  - Dr. Nicholas Coops, Dr. Thomas Hilker,
    Danny Grills, Martin van Leeuwen, Chris Bater

Partners: WFM - Hinton Wood Prod.; Alberta SRD; CFS–PFC; UBC
Existing Data Sources & Evolving Objectives

LiDAR & Ground Data

- AB SRD: Full LiDAR coverage (2004-2007) @ 0.75 to 1.1 hits/m² & AVI data:

- HWP: Permanent Growth Sample Plot Data

Evolving Objectives

- Proof of Concept for mapping plot attributes from LiDAR-based predictions
Processing Point Cloud → “Canopy Metrics”

- Used available USDA FS Freeware package, “FUSION/LDV”, to tile, grid & calculate 61 Canopy Metrics @ 25m X 25m resolution (i.e. for each of nearly 14 million grid cells)
HWP maintains a network of systematically distributed *Permanent Growth Sample Plots*
- team used 788 of >3200 available plots to develop Prediction Models
- Ordinary Least Squares multiple regression and a non-parametric tool *“Random Forests”* (resident in “R” statistical software) used to create prediction models
- separate models developed for each of 3 “forest types”, *based on AVI spp. composition*
  - “conifer-leading”, “mixed” & “deciduous-leading”
Predicted Inventory Variables → GIS Layers

- Mapped @ “plot-level” & @ AVI “polygon-level”
  - Top Height, Mean Height, & Modal Height
  - Quadratic Mean Diameter & Basal Area
  - Total & Merchantable Volume
  - Total Above Ground Biomass
- Also mapped all canopy metrics and several generalized plot/elevation characteristics
  - e.g. terrain wetness index, plan & profile curvature, solar radiation, hill shade, slope & aspect

Total Above Ground Biomass (tonnes/ha)
Merchantable Volume

- 525 m³/ha
- 0 m³/ha

- 33 m³/ha
- 384 m³/ha
- 276 m³/ha
- 247 m³/ha
- 164 m³/ha
- 14 m³/ha
- 331 m³/ha
Within-block variability:

Count: 365 cells
Minimum: 102 m$^3$/ha
Maximum: 480 m$^3$/ha
Mean: 276 m$^3$/ha
Std Dev: 70 m$^3$/ha
95% CI: 276 m$^3$/ha ± 7.18 m$^3$/ha

Merchantable Volume
# Validation

Weight-scaled volume from 272 cutblocks harvested since LiDAR acquisition compared to predictions from LiDAR & Cover Type Adjusted Volume Tables

<table>
<thead>
<tr>
<th>Block Size (m³ X1000)</th>
<th>Source of Prediction</th>
<th>Predicted Volume – Scaled Volume</th>
<th>Statistically significant?</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 5 n = 138</td>
<td>LiDAR CT Vol. Table</td>
<td>-6.7% -23.7%</td>
<td>No Yes</td>
</tr>
<tr>
<td>5 – 10 n = 76</td>
<td>LiDAR CT Vol. Table</td>
<td>+1.8% -17.4%</td>
<td>No Yes</td>
</tr>
<tr>
<td>10 – 15 n = 25</td>
<td>LiDAR CT Vol. Table</td>
<td>-1.2% -22.3%</td>
<td>No Yes</td>
</tr>
<tr>
<td>15 – 20 n = 15</td>
<td>LiDAR CT Vol. Table</td>
<td>-4.4% -23.5%</td>
<td>No Yes</td>
</tr>
<tr>
<td>&gt;20 n = 18</td>
<td>LiDAR CT Vol. Table</td>
<td>+6.6% -17.4%</td>
<td>No No</td>
</tr>
</tbody>
</table>

Information courtesy Hinton Wood Products A division of West Fraser Mills Ltd.
Conclusions

• Using LiDAR technology, we can:
  – Directly measure tree heights
  – Calculate accurate estimates of stem volume and basal area
    • Accurate plot data is CRITICAL to accurate estimations of forest attributes
      – GPS location of plot centers
      – Short time lag between field measurements and LiDAR data collection

• LiDAR technology is continuing to improve
  – More pulses per square meter (from 4 to 8 to 12)
    • More accurate tree heights
    • Easier to identify individual trees
  – Methods to process LiDAR data are improving as well
Thank you

doug.k.bolton@alumni.ubc.ca
rory.tooke@ubc.ca
nicholas.coops@ubc.ca
References


