Airborne Laser Scanning (ALS) for forestry applications

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http://www.ipf.tuwien.ac.at/
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Outline

• Which data are required in forestry?
• What is the main output of ALS for forestry applications?
• Which approaches are commonly applied?
• What is the advantage of ALS for the derivation of forest parameter?
• Which accuracies can be derived?
• Who uses ALS for operational forestry applications?
• Which limitations of ALS for operational forestry applications exist?
• Outlook to new ALS sensors and their benefit for forestry applications?
Which data are required for forestry?

- Foresters have to know what is where?
- What is the size of the forest stands?
- Which tree species are available?
- How many trees per hectare are available?
- What is the crown cover, tree height, diameter at breast height?
- How much biomass is available within a forest stand?
- ...

- These information are the basis for
  - Economic and ecologic forest management and planning
  - Forest policy
  - Scientific studies
  - Management of renewable resources
  - Etc. …
Which information from ALS is important for forestry applications?

• Common ALS-systems record the first and the last backscattered echoes
• The difference heights between the first and the last echoes represents tree heights

→ ALS delivers quantitative measurements!
Topographic models from ALS data

- Classification of each laser point into terrain and off-terrain points
- Calculation of topographic models (DSM, DTM)
- Calculations of the normalized digital surface model (nDSM)
- A common spatial resolution of these models is 1m
- The nDSM represents objects heights (buildings, trees, …)
Photogrammetry versus Laserscanning (I)

ACTIVE
Airborne Laserscanning

versus

PASSIVE
Photogrammetry

→ Advantage for the derivation of the terrain within forested areas!
Photogrammetry versus Laserscanning (II)

nDSM

Orthophoto

nDSM

> 30.0 m

0.0 m

0 45 90 180 Meters

0 45 90 180 Meters
Canopy Height Model (CHM = DSM – DTM)
• Forest area mapping based on 3D-Laser Points
  - E.g.: segmentation of the 3D-point cloud
  - Classification of the derived segments
  - High point density is required; time consuming computations!
• **Pixel-based forest area mapping based on the nDSM**
  - E.g.: nDSM > 2M → forest, buildings
  - Removal of buildings (e.g. roofs → smooth surface; forests → rough surface)
  - Removal of small forest areas (e.g. minimum mapping unit 50m²)
  - Smoothing of forest borders (e.g. morphological operations)
• **Object-based forest area mapping based on the nDSM**
  - Segmentation of the nDSM (e.g. watershed, region growing, …)
  - Object-based classification of the derived segments
  - Removal of small forest areas (e.g. minimum mapping unit 50m²)
  - Smoothing of forest borders (e.g. morphological operations)
Forest area mapping (IV)

- Object-based land cover classification based on ALS (nDSM) and orthophotos (e.g. eCognition, …)

CIR Orthophoto  ALS Heights (nDSM)  Classification

Hollaus et al. (2005) Advances in Geosciences, 5, 57-63
Forest parameter from ALS data

- Two approaches
  - Single-tree-based
    - Higher ALS point density is required (e.g. > 4 points/m²)
    - Sensitive regarding differences in the point density and the acquisition time
    - Derivation of forest parameter without reference data possible
    - Time consuming computations
    - Commonly used for small study areas (e.g. urban vegetation, …)
  - Area-based (plot-/stand-level)
    - Reference data (e.g. national forest inventory data) are required to calibrate the empirical models
    - More robust than single-tree-based approaches
    - Already in use for operational applications
Forest parameters for single trees

- Detection of single trees
- Tree height estimation
- Estimation of tree crown diameter
- Diameter at breast height (dbh)
- Tree species
Detection of single trees

- Local maxima filters → tree tops
- Tree crown segmentation → tree crowns

(Maier & Hollaus 2006)
Tree heights

• Extracting tree heights based on
  ▪ First-echo 3D-points (or the DSM) and DTM
  ▪ Search the highest first-echo point inside a radius (depending on the tree height)
  ▪ Subtract the terrain height from the highest first-echo point

<table>
<thead>
<tr>
<th>ID</th>
<th>X[m]</th>
<th>Y[m]</th>
<th>tree height [m]</th>
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<td>202855.47</td>
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<td>-31302.68</td>
<td>202855.65</td>
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<td>13</td>
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<td>202863.57</td>
<td>31.5</td>
</tr>
</tbody>
</table>
Practical problems for single-tree parameter estimations

Interlocked trees
6 single trees are interlocked to 2 groups

Dense forests
If ALS data have a low point density – single trees can hardly be detected

Leaning trees
An overestimation of the tree heights occurs (yellow line)
**Tree crowns**

- **Estimation of tree-crown diameters**
  - Calculation of the mean diameter of the derived tree-crown segments (e.g. mean diameter, smallest enclosing circle, …)
  - Based on the tree-crown area
    \[ L = \sqrt{\frac{4A}{\pi}} \]
  - Fitting rotating ellipsoids
    (Vögtle & Steinle, 2004)
  - Fitting fourth order polynomial functions
    (Popescu et al., 2003)
Diameter at breast height / stem volume

• Assessment of diameters at breast height (1.3 m) → \( dbh \)
  ▪ Based on empirical functions
    ◆ E.g.: \( dbh = f_{(\text{tree height, crown diameter})} \)
    ◆ E.g.: \( dbh = f_{(\text{tree height, crown diameter, tree species})} \)

• Stem volume
  ▪ Based on empirical functions
    ◆ E.g.: Stem volume = \( f_{(\text{tree height, dbh, tree species})} \)
Tree species

- For different tree species typical tree crown models can be found in the literature.
- Fitting these models into the 3D-ALS point cloud → best fit → tree species.
- Tree species classification based on the vertical distribution of the laser points.
Application of single-tree specific parameters

- A digital model of the forest derived from ALS can be used for
  - Forest management and planning activities
  - Ecological studies
  - Fire behavior modeling
  - Basis for a urban tree cadastre
  - Visualizations
  - …
Area-based forest parameters

- Crown cover / structure types
- Stand heights
- Stem volume
- Biomass
Crown cover / structure types (I)

- Segmentation of the nDSM
  → derive areas with homogenous canopy heights
- Classification based on canopy heights

(Maier B. et al. 2007)
Crown cover / structure types (II)

- Meta-segmentation → forest stands
- Classification → forest structure for each forest stand

### Table: Forest Structure Types

<table>
<thead>
<tr>
<th>Rule set</th>
<th>Structure type</th>
<th>No. of Stands</th>
<th>Area in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>HC1 &gt; 50%</td>
<td>Young growth</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Division Index &gt;= 0.75; HC2 or HC3 &gt; 50% or two HC with &gt; 30%</td>
<td>uniform dense</td>
<td>18</td>
<td>36</td>
</tr>
<tr>
<td>Division Index &lt;= 0.75; HC2 or HC3 &gt; 50% or two HC with &gt; 30%</td>
<td>uniform open</td>
<td>11</td>
<td>9</td>
</tr>
<tr>
<td>Division Index &gt;= 0.75; no HC &gt; 50% and not two other HC with &gt; 30% and CD &gt; 20%</td>
<td>multilayered dense</td>
<td>14</td>
<td>27</td>
</tr>
<tr>
<td>Division Index &lt;= 0.75; no HC &gt; 50% and not two other HC with &gt; 30% and CD &gt; 20%</td>
<td>multilayered open</td>
<td>29</td>
<td>26</td>
</tr>
<tr>
<td>CD &lt; 20%</td>
<td>opening</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>78</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

(Maier B. et al. 2007)
Crown cover / structure types (III)

• Mapping the forest structure types for large areas

Figure 8. Distribution of discrete structure types (Maier B. et al. 2007)
Forest stand heights

• Based on the nDSM

• The outline of the forest stands can be generated from the ALS data or can be taken from a GIS

• Mean heights, median height, …
Lorey’s mean height

- Lorey’s mean height is the mean tree height weighted by the basal areas.
- Basal area is the cross section area of a tree at breast height (1.3m above ground level).

![Graph showing Lorey's mean height](image)

**Example:**
- For the sample plot number 459, the canopy height at 88% corresponds to the Lorey’s mean height.
Stem volume estimation

- The estimation of stem volume is based on empirical models
- For the calibration of the models reference data are required
  - E.g. national forest inventory data
  - E.g. The National Forest Inventory (NFI) of Austria is based on permanent, regularly distributed sample plots with a distance of 3.89 km
  - Each grid point (tract) consists of 4 Angle gauge sample plots
Example Vorarlberg: NFI data

- Entire district of Vorarlberg
  - 2 604 km² entire area
  - 970 km² forest area
  - Altitudes: 396 - 3312 m

- NFI data
  - 132 Bitterlich plots
  - Tree-based parameter
    - Position, species, bhd, height
  - Area-based parameter
    - Stem volume [m³/ha]
Example Vorarlberg: ALS data

- Data acquisition within the framework of a commercial terrain mapping project
- Acquisition time: 2002-2004
- Higher altitudes in summer under snow-free conditions
- Lower altitudes in autumn, winter, spring with leaf-off condition
- Point densities: 1-4 p/m²
- Flying heights: ~650 to 2000 m
- Different ALS sensors: Optech ALTM 1225 & 2050, Leica ALS50
- Complex flight pattern due to the difficult topography
- Exact georeferencing is required
- The derived topographic models (DTM, DSM, CHM) have a spatial resolution of 1 m
Empirical stem volume model: concept

- **Stem volume = f(canopy volume)**

$$v_{\text{stem,fi}} = \sum_{i=1}^{n} \beta_i \cdot v_{\text{can,i}}$$

$$v_{\text{can,i}} = f_{\text{first-echo,i}} \cdot c h_{\text{mean,i}}$$

- $v_{\text{stem,fi}}$: Stem volume - forest inventory data [m³/ha]
- $\beta_i$: Unknown model parameters
- $n$: Number of canopy height classes
- $v_{\text{can,i}}$: Canopy volumes for the canopy height classes $i$ [m³/ha]
- $c h_{\text{mean,i}}$: Mean canopy height for the canopy height classes $i$ [m]
- $f_{\text{first-echo,i}}$: Percentage of first echoes within the canopy height class $i$ [-]

- $V_{\text{can}}$ calculated from CHM of Ø20m around center NFI plot
Calibration of the stem volume model with NFI sample data
The stem volume estimation is based on the 3D first echo laser points

\[
\begin{align*}
\text{ALS - Holzvorrat [m}^3/\text{ha]} & \quad \text{ÖWI - Holzvorrat [m}^3/\text{ha]} \\
\end{align*}
\]

\[R^2 = 0.79\]
\[SD [%] = 30.2\]
Stem volume model – calibration (II)

- Calibration of the stem volume model with NFI sample data
  The stem volume estimation is based on the nDSM (pixel size 1m)
Stem volume map

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Stem Volume

> 800 [m³/ha]

0 [m³/ha]
Validation

Stand Montafon: ~500 sample plots
ø 465 m³/ha

ALS: 6 560 ha
Total: 2 773 300 m³
ø 423 m³/ha

ALS: 23 070 ha
Total: 9 656 900 m³
ø 419 m³/ha
Application

Stem volume map

Outlines of forest stands
Sample plots

Holzvorrat pro Bestand

© Landesvermessungsamt Feldkirch & Stand Montafon Forstfonds

Holzvorrat
> 600 m³/ha
0 m³/ha

© Landesvermessungsamt Feldkirch & Stand Montafon Forstfonds

ALS for forestry applications
Summary and outlook

- **Multiple-shift usage of ALS data**
  - Topographic models (DTM, DSM), buildings, power lines, parameters for vegetation, …
  - Competition between ALS data acquisition companies → decreasing data costs → quality!!

- **Operational parameters from ALS**
  - Forest area mapping
  - Single tree detection – if the ALS point density is high enough (e.g. > 5 points/m² → depending on the forest types / structure)
  - Tree height estimation
  - Stand heights, crown cover, …
  - Stem volume / biomass estimation for large areas

- **Future work**
  - Transfer of the presented algorithms to deciduous forests
  - Use of new laser scanner sensors e.g. Full-Waveform laser scanner data (amplitude, echo width, backscatter cross-section, …)