LiDAR for vegetation applications

UoL MSc Remote Sensing

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Introduction

• Introduction to LiDAR RS for vegetation
• Review instruments and observational concepts
• Discuss applications arising for measuring and monitoring vegetation
  – primarily forests
Why LiDAR?

• Main reason:
  – (relatively) direct measurement of tree/canopy height
  – Tree height strongly correlated to other properties
    • Woody biomass
    • Age etc.

• BRDF and other radiometric RS
  – Need to infer properties from signal
Alternative technologies

- Stereo Photogrammetry
  - Tree height in sparse canopies
    - Need to extract ground height

- InSAR
  - Scattering height not directly canopy height
    - Density, wavelength, polarisation
  - Need to subtract ground height
Fig. 6. Canopy height models (CHM’s) of Monks Wood National Nature Reserve. (a) dual-wavelength InSAR CHM; (b) LIDAR CHM (validated using theodolite: rmse=2.15 m). Color scale: 0…25 m.
Basis of LiDAR measurement

- \( t = \frac{2 \cdot d}{c} \)
- \( h = d_1 - d_2 = \frac{c}{2} (t_1 - t_2) \)
- \( c = 299.79 \times 10^6 \text{ m/s} \)
  - i.e. 4.35 ns flight time per m
Wavelength

- Typically use NIR 1064 nm
- Green leaves scatter strongly
- Atmospheric transmission high
Platform and scanning

- Requires precise knowledge of platform location and orientation
  - GPS
  - INS
- Typically mirror scanning
  - On aircraft
Types of LiDAR system

- Discrete return
- ‘Waveform’
## Discrete return LiDAR

- **Airborne**
- **Small footprint**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Typical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength(^a)</td>
<td>1.064 μm</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>5–15 kHz (50 kHz max)</td>
</tr>
<tr>
<td>Pulse energy</td>
<td>100s μJ</td>
</tr>
<tr>
<td>Pulse width</td>
<td>10 ns</td>
</tr>
<tr>
<td>Beam divergence</td>
<td>0.25–2 mrad</td>
</tr>
<tr>
<td>Scan angle (full angle)</td>
<td>40° (75° max)</td>
</tr>
<tr>
<td>Scan rate</td>
<td>25–40 Hz</td>
</tr>
<tr>
<td>Scan pattern</td>
<td>Zig-zag, parallel, elliptical, sinusoidal</td>
</tr>
<tr>
<td>GPS frequency</td>
<td>1–2</td>
</tr>
<tr>
<td>INS frequency</td>
<td>50 (200 max)</td>
</tr>
<tr>
<td>Operating altitude</td>
<td>500–1000 m (6000 m max)</td>
</tr>
<tr>
<td>Footprint</td>
<td>0.25–2 m (from 1000 m)</td>
</tr>
<tr>
<td>Multiple elevation capture</td>
<td>2–5</td>
</tr>
<tr>
<td>Post spacing</td>
<td>0.5–2 m</td>
</tr>
<tr>
<td>Accuracy (elevation)</td>
<td>15+ cm</td>
</tr>
<tr>
<td>Accuracy (planimetric)</td>
<td>10–100 cm</td>
</tr>
<tr>
<td>Post-processing software(^b)</td>
<td>Proprietary</td>
</tr>
<tr>
<td>Price (standard)</td>
<td>US$850K–$1,000K</td>
</tr>
<tr>
<td>Price (custom)</td>
<td>US$1,000K–$2,000K</td>
</tr>
<tr>
<td>Delivery (standard)</td>
<td>20–26 weeks</td>
</tr>
</tbody>
</table>

**Notes:**

\(^a\)Generally diode-pumped Nd:YAG, Nd:YLF and Nd:YVO\(_4\), although there are some systems operating at 1.5 μm.

\(^b\)Refers to geo-referencing of laser slant ranges to an established reference frame, normally WGS84.
Small footprint

- beam high chance of penetrating holes in a vegetation canopy
  - to provide ground samples
- height measurement more easily associated with a single ‘object’
  - rather than blurred over some area
  - i.e. greater chance of hitting a ‘hard’ target.

- e.g. 0.1 mrad from 1000 m giving a footprint of around 10 cm at nadir
Small footprint

- Chance may miss tree tops
  - Horizontal sampling important
- May double count

Fig. 5. Tree height variance can be inflated due to misperceived tree heights (from large post spacing) within the tree height-finding model. (a) Height of trees 1 and 3 is measured correctly because LiDAR returns intercept tree peaks (yellow). Height of tree 2 is incorrectly measured because the LiDAR return is from the side of the crown (blue). (b) Tree 4 is counted as two stems (and heights) due to a forked or irregular tree crown.
Discrete return LiDAR

- Most modern systems:
  - First and last return
  - need to distinguish crown/ground points
Crown/ground points

- Can use e.g. local minima to determine ground
- And/or intensity of return
Complicating effects

- High slope can complicate local minima filtering
- As can any understorey
Waveform LiDAR

- Sample returned energy
  - Into equal time (distance) bins
Use larger footprint (10s of m)

- Backscattered energy low
  - Increased signal (integral over area)

- Enable measurement of whole tree (canopy)
  - and ground

- Trade-off with slope effects
Ground signal more spread for slope (or roughness)

More likely to become mixed with canopy signal for higher slopes
GLAS on IceSat: 70 m footprint

- ground slope of $10^\circ$
  - ground signal to be spread over $70\tan10^\circ$
  - 12.34m
- complicates ability to retrieve canopy information over anything but very flat ground
  - $5^\circ$ for GLAS?

- LVIS: 25 m footprint
  - Apparently little real slope effect (4.4 m spread for $10^\circ$)
  - Same order effect as other uncertainties
    - Position
    - multiple scattering
    - Gaussian energy distribution across footprint
Example systems: Discrete Return

- Cambridge University
  - Optech ALTM 3033 LiDAR
    - Piper Navajo Chieftain aircraft
- 33,000 obs per s
- first and last returns and intensity
- operating altitude of 1000 metres
  - RMS ht. accuracy of < +/- 15cms
- made available to NERC ARSF
Other UK operators

- Environment Agency
- Infoterra
  - using similar systems

- Airborne Discrete return LiDAR very much operational system
- Most information extraction simple height maps
  - But multitude of practical uses for these
Waveform LiDAR

- **SLICER**
  - NASA instrument
  - 1990s+

*Figure adapted from B. hill, Harding, NASA/GSF*
SLICER

- swath of five 10-m diameter footprints
- waveform 11 cm vertical sampling (0.742 ns)
- and can be flown at relatively high altitudes
  - e.g. 5000m AGL in Means et al, 1999
- Horizontal positioning accuracy is around 5-10m
- Larger receiver telescope than illuminated beam
Multiple scattering

- Large footprint, particularly larger receiver gives rise to multiple scattering influence on signal

- Visible as below-ground signal
First order scattering
With multiple scattering
Measurement

SLICER forest measurements and modelling

Note magnitude of ground returns
Very ‘rich’ 3D dataset

Figure 3. Measurements of canopy structure made using NASA’s SLICER (Scanning Lidar Imager of Canopies by Echo Recovery) device. Panel a shows ground topography and the vertical distribution of canopy material along a 4-km transect in the H. J. Andrews Experimental Forest, Oregon. Each column is the width of one laser pulse waveform. Panels b, c, and d show close-ups of the canopies of three 550-m transects in young, mature, and old-growth Douglas fir–western hemlock forest stands, with their ground elevations adjusted to a uniform level.
Vegetation Canopy LiDAR (VCL)

Spaceborne concept

Also CARBON-3D concept
(with multi-angular spectroradiometer)
LVIS (Laser Vegetation Imaging Sensor)
Airborne simulator for VCL
25 m footprints with 20 m along- and across-track sampling.
LVIS data product
GLAS (Geoscience Laser Altimeter System) LiDAR, launched in 2003.

70 m footprint, so not designed for vegetation applications, although active area of research in recent years.

Figure 1. Observed forest maximum canopy height vs. ICESat estimates of same, for the three study areas and overall. See Table 2 for relevant correlation coefficients and RMSE.
Very rich source of information
EVI data provides strong separation between foliage profile (LAI), green height and stem profile (BA) – they are now analysed separately.
The data can be “sliced” by height providing stem plots and horizontal canopy slices.

Range Moments 18, 20 & 22 (for comparison)

Height Slices 0.25, 1.75 & 3.75 m above EVI provide stem information.

CSIRO Marine & Atmospheric Research (CMAR)
### Information Extraction

<table>
<thead>
<tr>
<th>Forest Characteristic</th>
<th>Lidar Derivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canopy Height</td>
<td>Direct retrieval</td>
</tr>
<tr>
<td>Subcanopy Topography</td>
<td>Direct retrieval</td>
</tr>
<tr>
<td>Vertical distribution of intercepted Surfaces</td>
<td>Direct retrieval</td>
</tr>
<tr>
<td>Aboveground Biomass</td>
<td>Modeled</td>
</tr>
<tr>
<td>Basal Area</td>
<td>Modeled</td>
</tr>
<tr>
<td>Mean Stem Diameter</td>
<td>Modeled</td>
</tr>
<tr>
<td>Vertical Foliar Profiles</td>
<td>Modeled</td>
</tr>
<tr>
<td>Canopy Volume</td>
<td>Modeled</td>
</tr>
<tr>
<td>Large Tree Density</td>
<td>Inferred</td>
</tr>
<tr>
<td>Canopy Cover, LAI</td>
<td>Fusion with other sensors</td>
</tr>
<tr>
<td>Life Form Diversity</td>
<td>Fusion with other sensors</td>
</tr>
</tbody>
</table>
Direct Measurements

- canopy height, sub-canopy topography and vertical distribution of intercepted surfaces
- direct or near-direct information from LiDAR
- either of the LiDAR systems considered here
  - (discrete return and waveform)
Caveats

• discrete return systems
  – forest density is not too high

• for both: complicating factors
  – e.g. high slopes, very rough ground or sub-canopies
  – slope only important to small footprint systems for local spatial operations
    • e.g. local minima filtering
Caveats

• ‘hit’ may not come very top of a tree
  – tree shoulders in discrete return down-bias estimates of canopy height
  – Impact varies with tree shape and density
    • e.g. more problematic for conical trees
    • apply some calibration to LiDAR-measured tree heights
      – particularly from discrete return systems
    • other methods e.g. use upper 10% or so of heights
Caveats

- waveform systems have larger footprints
  - can be difficult to defining tree height at such scales
  - One technique use the top five tree heights of a plot
    - (a common measurement in forestry)
    - since this is what a large footprint lidar would see.

- if locational accuracy order of 5-10m
  - Can be difficult to locate trees precisely for ground comparisons
Canopy vertical distribution

- Waveform LiDAR:
  - Vertical distribution of intercepted elements
  - Need to convert to vertical distribution of LAI/biomass

- If assume first-order scattering only
  - with a spherical angular distribution
  - with no clumping (as is usually the case)
    - straightforward to calculate required attenuation terms
    - and transform the signal into an estimate of the vertical vegetation profile

- More complex to account for other effects
  - Need RT model
  - And possibly other sources (e.g. multi-angular hyperspectral)
Empirical relationships

- Canopy height strongly related to
  - Basal area
  - Stem diameter
  - Biomass
  - Timber volume etc.

- Through allometric relations used in forestry
- Many empirical models linking these.
Canopy Cover

• Various attempts at this
  – E.g. waveform:
    • soil peak relative to vegetation signal
Tree number density

• Tree counting
  – From discrete return systems
  – Local maxima & minima
    • Ground and crown
  – High resolution classification of e.g. NDVI
Popescu et al., 2003 http://filebox.vt.edu/users/wynne/Popescu%20et%20al%202003%20crown%20diameter%20CJRS.pdf

Figure 4. Orthoimage (a) and tree tops identified in the hardwood stand (b) and the pine plantation (c). Rectangles on the orthoimage show approximate locations of zoom windows (b) to the left and (c) to the right. Plantation row pattern oriented SW–NE is visible in (a) and (c). (Popescu and Wynne, 2001, © 2001 American Society for Photogrammetry and Remote Sensing, 2001 Annual Conference Proceedings).

Figure 5. Flow chart of algorithm for measuring crown diameter.
Figure 6. Vertical profiles through the CHM and the fitted polynomials for a deciduous tree and a pine located in the center of the CHM "image" (a) and (b), respectively. Vertical profiles along the horizontal direction for the deciduous and the pine trees are shown in (c) and (d), and (e) and (f) are vertical profiles along the vertical direction for deciduous and pine trees, respectively.
Radiative Transfer modelling and Inversion

- Various attempts at RT LiDAR modelling
  - RT (Sun and Ranson)
  - Ray tracing (Govaerts, Lewis)
  - GORT (Ni-Meister)

- Interesting recent attempt at RT model inversion
  - Koetz et al. 2006
Fig. 2. Performance of the model inversion for the synthetic dataset. Circles represent the median of possible solutions, and error bars represent the uncertainties related to the model inversion (standard deviation of possible solutions).
RT Inversion

Fig. 3. Performance of the model inversion for the SNP dataset. Circles represent the median of possible solutions, and error bars represent the uncertainties related to the field measurements and model inversion (standard deviation of possible solutions).
Conclusion

• Two types of LiDAR system
  – Discrete return, waveform

• Discrete return (small footprint)
  – Standard monitoring instrument from aircraft platforms
  – Range of useful parameters can be derived

• Waveform (large footprint)
  – More experimental
  – But very rich source of data on 3D structure