Dual-baseline Polarimetric SAR Tomography for Tree Height Estimation Using Single-Pass L-Band PolInSAR Data

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Outlines

- Objectives
- System
- Data processing
  - Wavenumber-domain
  - Time-domain
- Methodology for tree height estimation
  - Dual-baseline SAR tomography
- Results
  - Underlying ground and tree top heights
  - Compared with single-baseline PolInSAR inversion techniques
  - Validation against Lidar data
- Conclusion
Climate change context:

- 4 billion ha (30%) of global land cover is forested
- Within these forests about 72 t/ha carbon are sequestered in above-ground biomass (global mean)
- *Forest destruction believed responsible for almost 20% of CO2 annual emissions*
  - Greater than the total transport industry contribution globally
Baseline biomass measurements require improvement in:
- spatial resolution (to 0.5 ha)
- coverage (particularly the tropics)
- accuracy (goal 20%)

Objective of this work is to demonstrate biomass measurement with single-pass airborne L-Band Pol-InSAR
## Single-pass L-Band PolInSAR System

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak power</td>
<td>0.4 kW</td>
</tr>
<tr>
<td>Wavelength</td>
<td>0.2262 m</td>
</tr>
<tr>
<td>Polarization</td>
<td>quad (HH, HV, VH, VV)</td>
</tr>
<tr>
<td>PRF (per channel)</td>
<td>2200 Hz</td>
</tr>
<tr>
<td>max. system bandwidth</td>
<td>up to 135 MHz (80 MHz nominally)</td>
</tr>
<tr>
<td>range resolution</td>
<td>up to 1.1 m</td>
</tr>
<tr>
<td>azimuth resolution</td>
<td>0.25 m</td>
</tr>
<tr>
<td>typical flight altitude</td>
<td>1000 m</td>
</tr>
<tr>
<td>swath width</td>
<td>1.2 km</td>
</tr>
<tr>
<td>interferometric baseline</td>
<td>3.5 m</td>
</tr>
<tr>
<td>NESZ</td>
<td>&lt; -40dB</td>
</tr>
</tbody>
</table>

- Assembled in 2007
- Gulfstream Commander platform
- Radar hardware based on previous X- and P-Band TopoSAR system
- Antennas mounted on rigid beam passing through the un-pressurized part of the fuselage
Data processing

Dual-line motion compensation

Raw data -> Wavenumber domain focus

Time-domain back projection

Image focusing -> Geo & Polar Calibration

Calibration -> Freq-domain SLC

Time-domain SLC

Focusing performance

- Interferometric performance, channel mis-registration, coherence
  (Schwaebisch et al, IGARSS 2010)
- Tomographic focusing
In our experimental L-Band system, pulses were recorded in both ping-pong and non ping-pong modes simultaneously.

- 12 active channels were recorded

This provided three independent antenna phase center positions (noted as NN-NF-FF) in a single flight.

- Dual-baseline configuration
Dual-baseline Configuration

**Full Baseline: NN-FF**

\[ \phi_{nn,ff} = \frac{4\pi}{\lambda}(r_1 - r_2) \]

**Half Baseline: NN-NF**

\[ \phi_{nn,nf} = \frac{2\pi}{\lambda}(r_1 - r_2) \]

\[ \phi_{nn,ff} = 2\phi_{nn,nf} \]
Dual-baseline PolInSAR Signal Model

Single source

- POLSAR unitary target vector
  \[ \mathbf{k} = [k_1, k_2, k_3]^T, \quad \mathbf{k}^\dagger \mathbf{k} = 1 \]
- Polarimetric steering vector
  \[ \mathbf{a}(z, \mathbf{k}) = \mathbf{k} \otimes \mathbf{a}(z) \]
- 3-M element MB-POLInSAR signal
  \[ \mathbf{y}_P(l) = \begin{bmatrix} y_1(l) \\ y_2(l) \\ y_3(l) \end{bmatrix} = s(l)\mathbf{a}(z, \mathbf{k}) + \mathbf{n}(l) \]

D sources

- Polarimetric steering matrix
  \[ \mathbf{A}(\mathbf{z}, \mathbf{K}) = [\mathbf{a}(z_1, k_1), \ldots, \mathbf{a}(z_D, k_D)] \]
- 3-M element MB-POLInSAR signal
  \[ \mathbf{y}_P = \mathbf{A}(\mathbf{z}, \mathbf{K})\mathbf{s} + \mathbf{n} \]
Polarimetric Tomographic Techniques

- FP-Beamforming:
  \[
  P(z) = \frac{\lambda_{\text{max}}(B^H(z)RB(z))}{m^2}
  \]
  \[
  B(z)^H R B(z) k_{\text{max}} = \lambda_{\text{max}} k_{\text{max}}
  \]

- FP- Capon:
  \[
  P(z) = \frac{1}{\lambda_{\text{min}}(B^H(z)R^{-1}B(z))}
  \]
  \[
  B(z)^H R^{-1} B(z) k_{\text{min}} = \lambda_{\text{min}} k_{\text{min}}
  \]

- FP-Music:
  \[
  P(z) = \frac{1}{\lambda_{\text{min}}(B^H(z)E_n E_n^H B(z))}
  \]
  \[
  B(z)^H E_n E_n^H B(z) k_{\text{min}} = \lambda_{\text{min}} k_{\text{min}}
  \]

\[
B(z) = \begin{bmatrix}
  a(z) & 0 & 0 \\
  0 & a(z) & 0 \\
  0 & 0 & a(z)
\end{bmatrix}
\]

Elevation: \( \hat{z} = \arg \max P(z) \)

Scattering mechanism: \( k_{\text{min}} \) or \( k_{\text{max}} \)
Global view of test sites
Test Site: Edson

- Test area near Edson: a forested region of Alberta, Canada
  - Patchwork of lodgepole pine forest and clearcut areas
  - Clearcuts may have been re-planted and in a regrowth phase
  - Typically 15-30 m high
  - L-Band data acquired in Nov. 2007 and again in June 2008

- Ancillary data
  - X-Band DSM (from 2006)
  - Lidar ground elevations and point cloud (courtesy Terrapoint Canada)
  - Color air photo (Valtus)
In our real dual-baseline case, Capon’s method merged ground and volume contributions in vertical direction;

**Combining Capon and MUSIC estimators**

- **MUSIC**: separate ground and volume centers: \( z_g \)
- **Capon**: approximate the vertical distribution of scatterers, truncate tree top height at -3dB from the volume center: \( z_{top} \)
Focus on trees higher than 10m, mask out short vegetations

Tomographic processing: order=1, bare; order=5, forested
Results at Near Range

Pauli-coded

Freq-domain data

Time-domain data

Black lines: LiDAR
Gray lines: SARTomo

Time-domain data provides more stable and precise estimates for ground and tree top.
Results at Mid-Far Range

Pauli-coded

Freq-domain data

Time-domain data

Black lines: LiDAR
Gray lines: SARTomo

Time-domain data provides much better tomographic focusing
Results at Far Range

Pauli-coded

Freq-domain data

Time-domain data

Black lines: LiDAR
Gray lines: SARTomo
Test zone

Airphoto

Lidar DTM

Lidar DSM

1150

1080 (m)
Georeferenced results from T-D data

Lidar

Tomographic results

Phase optimization algo.

DTM

1150

1080 (m)

DSM
Difference maps for DTM

Tomo DTM-Lidar DTM

Pha.opt DTM-Lidar DTM
Difference maps for DTM

Tomo DTM-Lidar DTM

Pha.opt DTM-Lidar DTM

Mask out bare areas, compare forested areas
Tomographic techniques have less overestimation for underlying ground
Difference maps for DSM

Tomo DSM-Lidar DSM

Pha.opt DSM-Lidar DSM
Difference maps for DSM

Mask out bare areas, compare forested areas
Tomographic techniques better than phase opt algorithms for tree top heights
Dif DTM = Tomo DTM - Lidar DTM

Dif DSM = Tomo DSM - Lidar DSM

<table>
<thead>
<tr>
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<th>Mean (m)</th>
<th>STD(m)</th>
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<tbody>
<tr>
<td>Dif DTM</td>
<td>2.58</td>
<td>1.65</td>
</tr>
<tr>
<td>Dif DSM</td>
<td>0.12</td>
<td>2.40</td>
</tr>
</tbody>
</table>
We can potentially obtain better results using dual-baseline SAR tomography, in terms of ground elevation recovery and tree height estimation.

The system suffered from multi-path affects, which makes both geometric and polarimetric calibration challenging.

The L-band dual-baseline configuration makes tomographic techniques challenging for the ground elevation estimation.
Acknowledgement