Forest Height and Ground Topography at L-Band from an Experimental Single-Pass Airborne Pol-InSAR System

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The L-Band Program Objective

To determine whether we can …

- Extract bare earth elevation (DTMs) beneath forest canopy and also extract the forest height,
- With adequate accuracy and consistency to justify an operational airborne system?

Some Considerations:

- L-Band vs P-Band
  - Forest Penetration
  - Bandwidth restrictions/Resolution (6 MHz vs 85 MHz)
- Single-Pass vs Repeat-Pass
  - Eliminate temporal decorrelation
  - Optimum baseline
- PolInSAR Algorithms
What is the Expected L-Band Attenuation?

2-Way Attenuation (db) vs Incidence Angle (80% ) for 20 meter Tree Height

Forest attenuation coefficients: Bessette and Ayasli (2001)
Under what conditions do we see the ground?

Forest Penetration Depth (HH) vs Incidence Angle Assuming NESZ = -30db; (80% of forest samples)

Forest attenuation coefficients: Bessette and Ayasli (2001)
Penetration depth definition: Kugler, et. al. (2006)

Desirable NESZ: -40 db
Objectives:

- Demonstrate DEM extraction performance in several sets of forest / topography conditions
- Learn enough to make sound recommendation for a potential operational follow-on system

Constraints:

- Inexpensive
- Rapid turn-around: one-year design / build / test window

Approach:

- Modify existing TopoSAR (X/P system)
  » Flexible digital architecture
- Maintain S/N performance (NESZ = -40 db)
  » Low power, low gain antennas
  » Fly low (1km), sacrifice swath (1km)
System Design

- Gulfstream Commander platform
- Radar hardware based on TopoSAR system
  - originally X- and P-band
- Antennas: log periodic
  - H and V planes
  - Mounted on rigid beam passing through the un-pressurized part of the fuselage
- Single Tx/Rx chain
  - Pulse sequential switching between polarizations and antennas
  - Monostatic and bistatic modes possible
    - Full and half baseline
    - Only full baseline discussed here
System Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>0.226 m</td>
</tr>
<tr>
<td>Max Bandwidth</td>
<td>135 MHz</td>
</tr>
<tr>
<td>Peak Power</td>
<td>0.4 kw</td>
</tr>
<tr>
<td>PRF/channel</td>
<td>2120 hz</td>
</tr>
<tr>
<td>No. of Channels</td>
<td>8, 12, 16</td>
</tr>
<tr>
<td>Polarization</td>
<td>Quad</td>
</tr>
<tr>
<td>Baseline</td>
<td>3.5 m</td>
</tr>
<tr>
<td>Test Altitude</td>
<td>1000 m</td>
</tr>
<tr>
<td>NESZ (max)</td>
<td>-40 db</td>
</tr>
<tr>
<td>Ground Swath</td>
<td>1100 m</td>
</tr>
<tr>
<td>Az. Res.</td>
<td>1.0 m</td>
</tr>
<tr>
<td>Slant Rg. Res</td>
<td>1.1 m</td>
</tr>
<tr>
<td>Incidence Angles</td>
<td>30 - 60 deg</td>
</tr>
<tr>
<td>$K_z @ 45^\circ$</td>
<td>0.14 rad/m</td>
</tr>
</tbody>
</table>
The PollInSAR Approach

- assume RVOG* model applicable,
- extract ground phase, $\Phi$, from the complex coherence

$$\tilde{\gamma}(w) = \exp\left[j\Phi \left(\frac{\tilde{\gamma}_{v_0} + m(w)}{1 + m(w)}\right)\right]$$

Extraction of Ground Phase and Canopy Height

To obtain ground phase, use:
- Coherence Mag. Optimization\(^{(1)}\)
  - for low vegetation
- Phase Optimization\(^{(2)}\)
  - for high vegetation

To obtain \( h_v \):
- use the inversion expression\(^{(3)}\)

\[
h_v = \frac{\text{arg}(\hat{\gamma}_{wv}) - \phi}{k_z} + \varepsilon \frac{2 \sin c \left| \hat{\gamma}_{wv} \right|}{k_z}
\]

Near Range

Far Range

\[ k_z = \left( \frac{4\pi}{\lambda} \right) \left( \frac{\Delta \theta}{\sin \theta} \right) = \left( \frac{4\pi B_n}{\lambda H \tan \theta} \right) \]

Optimum criterion for parameter inversion \(^{(1)}\)

\[ \left( k_z h_v / 2 \right) = 1.3 \]

\( k_z \) changes by \( x\ 6 \) across full swath

This presentation – will examine performance in far part of the swath

\( k_z = 0.10 \) to \( 0.05 \) rad/m

\( H_a \sim 60 \) to \( 120 \) m

\(~650\ m\)
$k_z$ vs ‘Design’ Canopy Height

‘Design’ $h_v = 2.6/k_z$

Near Range

Far Range

$\sim 650 \text{ m}$

$26 \text{ m}$

$13 \text{ m}$

$46 \text{ m}$
Geometric and polarimetric calibration components

Polarimetric calibration based on Quegan method:

- Range-dependent cross-talk and imbalance correction terms calculated using:
  - Trihedrals (10) placed across swath
  - Forest (flat, relatively homogeneous, extensive)

- Cross-talk (observed) less than -25 db
- HH/VV imbalance corrected across swath to
  - Amplitude 1.0 +/- 0.05
  - Phase 0.0 +/- 5 degrees

Test Program; Three sites in Western Canada

- Two areas in Alberta, Canada
  - **Edson**, Burnstick
  - Lodgepole pine species
  - 5 – 30 m heights
    » Various ages
    » Clearcut areas (bare or with recent regrowth
  - Winter, late spring acquisition

- One area in British Columbia, Canada
  - Fraser Delta
  - Several deciduous species
  - 15 – 40 m
  - Late spring acquisition

- Varying amounts of ground truth available
The Edson test area

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 February and again in June 2008

Ancillary data
- X-Band DSM (from 2006)
- Lidar ground elevations and point cloud (courtesy Terrapoint 2007)
- Color air photo (Valtus 2007)
Lidar ‘feature file’ or point cloud approx 1 sample/m²

The lidar canopy height ‘h_{100}’ is defined by the highest lidar sample value within a 5.6 meter search radius of each horizontal grid point (~100 m²)

A surface is then fitted to these points to represent the canopy smoothly

Lidar data provided by Terrapoint
Edson Test Site: Ancillary Data

<table>
<thead>
<tr>
<th>Air Photo</th>
<th>Lidar DSM</th>
<th>Lidar DTM</th>
<th>Lidar (DSM-DTM)</th>
</tr>
</thead>
</table>

- **Forest**: 15 – 30 m
- **Bare or regrowth (<5m)**

~1.3km

$X_{HH}(2006)$  
$L_{HH}$ (near ant)  
$L_{VV}$ (near ant)  
$L_{HV}$ (near ant)
Multipath Issues and Mitigation

During first set of tests (winter), severe multipath in one of the antennas limited the usable swath to the far half of the swath.

Subsequent absorber placement reduced the problem:
- Full swath available in summer tests
- Still some multipath effects seen in the magnitude images
- Interferometric phase effects handled by calibration (CORVEC)
- Some coherence magnitude impact

\[ \text{VV} \quad \text{VVVV} \]
\[ \text{Near} \quad \text{Far} \quad \text{Coherence} \]
Results

- Canopy height $h_v$
  - With respect to lidar canopy surface height $h_{100}$
- Ground elevation
  - With respect to lidar DTM
Profiles showing: **Lidar DTM, Lidar Canopy Height, L-Band h_v**

**Left Profile**

**Right Profile**

**M9054 (summer data)**
L-Band $h_{v}$ vs Lidar Canopy Heights ($K_z \sim 0.1$)

- Mean($\Delta$) = 0.5 m
- Stdvn($\Delta$) = 2.1 m

Mean($\Delta$) = -0.7 m
Stdvn($\Delta$) = 1.3 m
Lidar DTM, L-Band Ground (summer), Lidar Canopy Height, L-Band h_v (summer)
Lidar DTM, L-Band Ground (winter), Lidar Canopy Height, L-Band \( h_v \) (winter)

Cross Section

Left Profile

Right Profile

M9041 (winter data)
## Error Statistics: Edson Forest Samples (H>20m)

<table>
<thead>
<tr>
<th>Region</th>
<th>Type</th>
<th>Range</th>
<th>Mean±Std (m) DTM</th>
<th>Mean± Std (m) Canopy Height</th>
<th>Mean± Std (m) Lidar DSM Minus Bald DTM</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>Forest</td>
<td>Mid-Far</td>
<td>0.13 ± 2.50</td>
<td>15.45 ± 2.11</td>
<td>22.82 ± 1.21</td>
</tr>
<tr>
<td>F2</td>
<td>Forest</td>
<td>Mid-Far</td>
<td>2.17 ± 2.31</td>
<td>19.41 ± 1.48</td>
<td>24.59 ± 1.15</td>
</tr>
<tr>
<td>F3</td>
<td>Forest</td>
<td>Far</td>
<td>-1.55 ± 3.37</td>
<td>19.93 ± 1.59</td>
<td>23.27 ± 1.41</td>
</tr>
<tr>
<td>F4</td>
<td>Forest</td>
<td>Far</td>
<td>-2.37 ± 3.55</td>
<td>14.85 ± 0.91</td>
<td>22.39 ± 0.81</td>
</tr>
<tr>
<td>F5</td>
<td>Forest</td>
<td>Far</td>
<td>-1.82 ± 3.73</td>
<td>16.54 ± 1.55</td>
<td>23.32 ± 1.26</td>
</tr>
<tr>
<td>F6</td>
<td>Forest</td>
<td>Mid-Far</td>
<td>3.61 ± 2.98</td>
<td>19.27 ± 1.45</td>
<td>27.74 ± 1.01</td>
</tr>
<tr>
<td>F7</td>
<td>Forest</td>
<td>Far</td>
<td>1.68 ± 3.57</td>
<td>20.77 ± 2.08</td>
<td>26.52 ± 0.96</td>
</tr>
<tr>
<td>F8</td>
<td>Forest</td>
<td>Far</td>
<td>2.13 ± 3.12</td>
<td>20.08 ± 1.99</td>
<td>28.77 ± 0.80</td>
</tr>
</tbody>
</table>
Conclusions

- Results presented from tests of the first single-pass L–Band PolInSAR system
  - Edson test area – winter and early summer
  - 15-30 m tree heights
- Derived **forest heights** in center/far swath mostly consistent with lidar-derived canopy as shown in profiles (<1 meter bias)
  - Sampled areas show $h_v$(L-Band) ~ $h$(lidar) with standard deviation ~ 2 meters
  - Uncertain yet how robust this is over a larger range of tree heights, $k_z$, other forest types, etc
- **Ground elevations** noisier and exhibit local biases compared to lidar DTM
  - Mean offsets in local areas typ. 2-3 meters (winter data set), larger (summer data set) with standard deviation ~ 2.5 – 3.5 meters
- There is a summer/winter difference in the ground elevation accuracies
  - Not yet clear whether this is due to forest target changes or to system differences