Ground Topography Below Tropical Forests through Polarimetric SAR Tomography

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30/01/2019
Outline

- Interferometric height in tropical forest at P-band
  - Varying polarization
  - Varying biome
  - Varying incidence angle and ground slope
  - Varying phase-to-height conversion factor ($k_z$)
- DTM retrieval through SAR tomography
- Comparison with LiDAR DTM
  - Varying forest height
  - Varying ground slope
Topography through interferometry

SAR image pair  \hspace{1cm} \text{InSAR phase}  \hspace{1cm} \text{Elevation map}

Calibrated InSAR pair, phase flattened w.r.t. a reference elevation, for a distributed target:

\[ I_M = \int s(z) dz \quad I_S = \int s(z) e^{j \cdot k z \cdot z} dz \]

Target uncorrelated along \( z \):

\[ E[s(z)s^*(\xi)] = \sigma_s^2(z) \cdot \delta(z - \xi) \]

\[
\frac{E[I_M I_S^*]}{\sqrt{E[|I_M|^2]E[|I_S|^2]}} = \int \frac{\sigma_a^2(z)e^{-j \cdot k z \cdot z} dz}{\int \sigma_a^2(z) dz}
\]
Interferometric height

Interferometric coherence:

\[ \rho_{\text{int}} \triangleq \frac{E[I_M I_S^*]}{\sqrt{E[|I_M|^2]E[|I_S|^2]}} \]

\[ = \frac{\int \sigma_s^2(z) e^{-j \cdot k_z \cdot z} dz}{\int \sigma_s^2(z) dz} \]

Interferometric phase and elevation:

\[ \varphi_{\text{int}} \triangleq \angle \rho_{\text{int}} \]

\[ z_{\text{int}} \triangleq \frac{\varphi_{\text{int}}}{k_z} \]

E.g. three bright targets:

\[ \{ \varphi_1 = k_z \cdot z_1, \varphi_2 = k_z \cdot z_2, \varphi_3 = k_z \cdot z_3 \} \]

The integral becomes a finite sum:

\[ \varphi_{\text{int}} = k_z \cdot z_{\text{int}} \]

InSAR elevation

X-band \~3cm
C-band \~5cm
P-band \~70cm
Interferometric height with distributed targets

Interferometric coherence:

\[ \rho_{\text{int}} \triangleq \frac{E[I_M I_\ast_S]}{\sqrt{E[|I_M|^2] E[|I_S|^2]}} = \frac{\int \sigma_S^2(z) e^{-j k z \cdot z} dz}{\int \sigma_S^2(z) dz} \]

- \( \sigma_S^2(z) \) depends on polarization
- The vertical reflectivity intensity \( \sigma_S^2(z) \) takes into account the wave extinction too
- \( z_{\text{int}} \) results from a weighted average of complex exponential rather than height values directly
- For smaller \( k z \), \( z_{\text{int}} \) approaches the center of mass, higher \( k z \) moves \( z_{\text{int}} \) toward the peak of the distribution
Interferometric height maps

$z_{\text{int}}$ [m] - HH polarization

$z_{\text{int}}$ [m] - HV polarization

$z_{\text{int}}$ [m] - VV polarization

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>$\sim 75cm$</td>
</tr>
<tr>
<td>Tree top height</td>
<td>$\sim 35m$</td>
</tr>
<tr>
<td>Looks</td>
<td>121 (11x11 boxcar)</td>
</tr>
<tr>
<td>Height of ambiguity</td>
<td>Many (averaged)</td>
</tr>
</tbody>
</table>

$z_{\text{int}}$:
- Can reach up to 25m above the ground
- HH polarized wave exhibits significant penetration w.r.t. HV or VV
Interferometric height for different tropical forests

Paracou (TropiSAR ONERA)

La Lopé (AfriSAR DLR)

Mabounie (DLR AfriSAR)

$z_{int}$:

- The “hole” due to the double-bounce scattering mechanism is visible
- The quality of interferometric estimates depends on the biome
Interferometric height for different tropical forests

\[ z_{int} \]:
- Generally grows with the incidence angle
- This dependence depends on the biome too
Interferometric height for different tropical forests

Paracou (TropiSAR ONERA)

La Lopé (AfriSAR DLR)

Mabounie (DLR AfriSAR)

\[ z_{int} : \]
- Matches the center of mass for small baselines
- Gets closer to the peak of the distribution for larger \( k_z \)
Polarimetric SAR tomography

SAR tomography:
- Several interferometric SAR images
- A whole set of interferometric coherences is returned
- Focusing along z amounts to perform a spectral estimation
- A filtered version of $\sigma^2_z(z)$ can be recovered

SKPD$^{(1)}$ + AS$^{(2)}$ tomography:
- Ground and volume are separated
- The elevation of the ground can be read in the tomographic profiles


AfriSAR 2016 campaign (Gabon)

Features:
- Excellent calibration
- Ground as visible as the top canopy layer
- Ground elevation can be estimated
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Small Footprint LiDAR</th>
<th>Large Footprint LiDAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Footprint</td>
<td>~10 cm</td>
<td>~20 m</td>
</tr>
<tr>
<td>Platform</td>
<td>EC 135 (Helicopter)</td>
<td>B-200 (Airplane)</td>
</tr>
<tr>
<td>Sensor</td>
<td>Riegl VQ480U(1)</td>
<td>LVIS(2)</td>
</tr>
<tr>
<td>Ground extraction algorithm</td>
<td>“progressive triangulated irregular network densification”(3)</td>
<td>Peak of the lowest detected return</td>
</tr>
<tr>
<td>Areas</td>
<td>Rabi, Mondah</td>
<td>Mabounie</td>
</tr>
</tbody>
</table>


- Relatively young forest
- High variability in tree height (up to 50m)
- Some areas underwent significant disturbance

- Some regions are unavailable in the LiDAR map
- It might be due to a particularly thick forest
La Lopé

Small footprint LiDAR

TomoSAR DTM [m]

LiDAR DTM [m]

2km

600

500

400

300

2km

600

500

400

300

2km

600

500

400

300
Mabounié

TomoSAR DTM [m] vs. LiDAR DTM [m]

Large footprint LiDAR

2km
Comparison with LiDAR DTM

- **La Lopé**
  - $\sigma = 2.4m$
  - Small footprint LiDAR

- **Mondah**
  - $\sigma = 2.8m$
  - Small footprint LiDAR

- **Mabounie**
  - $\sigma = 5.6m$
  - Large footprint LiDAR
Mondah detail

Ground truth data are missing
LiDAR smooth reference
Difference between TomoSAR and LiDAR should not be interpreted as error
Conclusions

- InSAR phase center at P-band in tropical forests can lie several meters above the ground
- Height bias exhibit a non-linear dependence on
  - Phase-to-height conversion factor
  - Incidence angle
  - Ground slope
  - Polarization
- TomoSAR algorithms enable to locate the ground position below tropical forests at P-band
- TomoSAR DTMs quality is comparable to LiDAR DTMs
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Thanks for your attention!