Large-scale Mangrove Canopy Height Map Generation from TanDEM-X by Means of Pol-InSAR Techniques

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Coastal Blue Carbon

- The coastal ecosystems of **mangrove**, tidal marshes, and sea grass sequester and store significant amounts of coastal blue carbon from the atmosphere and ocean.
- Coastal blue carbon are now recognized for their role in mitigating climate change.
- Mangroves are...
  - a type of (sub)tropical forest.
  - salt tolerant plants found at the edge of land and sea and flooded regularly by tide.
  - the most carbon-rich forest in the tropics.
  - In the last 50 years, between 30-50% of mangroves have been globally lost: sea level rise, erosion, sea farm, illegal logging...

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**Figure 2.** Mean carbon storage above and belowground in coastal ecosystems versus terrestrial forest (Fourqurean et al. 2012; Pan et al. 2011; Pendleton et al. 2012).
Remote Sensing for Mangroves

- Access to coastal ecosystems such as mangroves for field surveys can be very expensive, difficult, and/or hazards. --> The availability of mangrove forest information is surprisingly missing!
- Remotely sensed observations of mangroves provide an alternative to field survey: **Passive & Active** sensors.

  - **Passive sensors**: Optic, near-infrared, infrared
    - Classify land cover types, vegetative species, vegetated health
    - Aerial photo, Landsat, MODIS, IKONOS, World-View
  - **Active sensors**: Synthetic Aperture Radar (SAR) and Lidar
    - Weather- and daylight-independent
    - 3-D vertical forest structure parameters retrieval (e.g. forest height, biomass)

- Mangrove canopy height information is a key parameter for ...
  - Estimating biomass
  - Understanding carbon dynamics
  - Land cover change
Remote Sensing for Mangroves

- Mangrove Height Estimation from space in previous works

SRTM

IceSAT/GLAS

- SRTM: 90 m by 90 m (currently 30 m resolution available)
- IceSAT/GLAS: about diameter of 60 m and interval of 172 m

- The coarse spatial resolution from SRTM and IceSAT/GLAS limits their modeling approaches to very large homogeneous mangroves.
- Although conventional repeat-pass SAR satellites have higher spatial resolution, temporal decorrelation is a critical issue for a successful forest height inversion.
TanDEM-X is a Great System for Mangrove Study!

- The first single-pass interferometric SAR satellite system (bistatic)
- Main objective: Global digital elevation model generation at 12-m spatial resolution
- Higher spatial resolution (SRTM, IceSAT/GLAS, Landsat series ...)
- Good $k_z$ range closed to equator ($25^\circ$N ~ $25^\circ$S) for mangrove height inversion:
  - Mangrove heights are relatively smaller than tropical forests.

- Shorter wavelength (3 cm) -> Weak ground contribution!
- Single-polarization (HH) -> Underdetermined problem!

Inversion?

Vertical wavenumber at the altitude

Published in: Florian Kugler et al.; IEEE TG&RS 2013
Mangrove Canopy Height Inversion

\[ \tilde{\gamma}(S_{TSX}S_{TDX}) = \frac{< S_{TSX}^* S_{TDX}^* >}{\sqrt{< S_{TSX} S_{TSX} > < S_{TDX} S_{TDX}^* >}} \]

\[
\tilde{\gamma}_{TSX/TDX} = e^{i\phi_0} \tilde{\gamma}_V \gamma_{SNR} \gamma_{Temp} \ldots
\]

\[ \tilde{\gamma}_V(f(z)) = e^{iK_z z_o} \int_0^{h_y} e^{iK_z z} f(z) \, dz \]

\[ \int_0^{h_z} f(z) \, dz \]

Volume Coherence

Decomposition

InSAR Complex Coherence

TSX SLC  TDX SLC  TDX  TSX

InSAR Phase  Coherence  InSAR Complex Coherence

… Vertical Reflectivity Function

TSX  SLAC  TDX  SLC
**Random Volume over Ground (RVoG) Model**

(Two-layer scattering model)

\[ f(z) = \tilde{m}_v e^{2\sigma z} + m'_G \delta(z - z_0) \]

- **Volume Coherence**
  \[
  \tilde{\gamma}_V = \frac{I}{I_0} \]
  \[
  I = \int_0^{h_v} e^{i\kappa z'} e^{\cos\theta_0 dz'} \\
  I_0 = \int_0^{h_v} e^{\cos\theta_0 dz'}
  \]

- **G/V Ratio:**
  \[
  m(\bar{w}) = \frac{m_G(\bar{w})}{m_v(\bar{w})I_0}
  \]

- **Vertical Wavenumber:**
  \[
  K_v^{z} = \frac{4\pi}{\lambda} \frac{\Delta \theta}{\sin(\theta_0)}
  \]

**Polarization**

<table>
<thead>
<tr>
<th>Polarization</th>
<th>Independent Complex Coherence</th>
<th>Assumption</th>
<th>Unknowns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quad-Pol.</td>
<td>[ \tilde{\gamma}(\bar{w}_1) \quad \tilde{\gamma}(\bar{w}_2) \quad \tilde{\gamma}(\bar{w}_3) ]</td>
<td>( m_3 = 0 )</td>
<td>( h_v, \sigma, \phi_0, m_1, m_2 )</td>
</tr>
<tr>
<td>Single-Pol.</td>
<td>[ \tilde{\gamma}(\bar{w}_1) ]</td>
<td>( m_1 = 0 )</td>
<td>( h_v, \sigma, \phi_0 )</td>
</tr>
</tbody>
</table>

**Condition:**

- **Unique solution**
- **Underdetermined problem**
Water Level Estimation in Mangroves

- Underlying topography in mangrove forests is negligible and flat due to the unique environment (i.e., water surface).
- Mangrove forest consists of vegetated area and open water body (e.g., rivers).

If double-bounce scattering, the two-bounce travel path of radar pulse = The one-bounce travel path on the water surface or on the bottom of mangrove trunk.

The interferometric phase represents the **GROUND PHASE** in the RVoG model.

Step-1: Boundary extraction
Step-2: Selection of double-bounce scattering pixels
Water Level Estimation: $Z_0$

- **SNR Decorrelation**
  - The actual SNR depends on the strength of the returned radar signal.
  - Extract *boundary* of mangrove forests

- **Coherent Scatterer (CS) technique**
  - Based on correlation coefficient between two parts of full image spectrum.
  - Select *stable targets* on the boundary

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$$\phi_0 = K_z Z_0$$

*Rafael Schneider et al (2006).*
TanDEM-X Mangrove Canopy Height Inversion Results

- Zambezi Delta (single image)
- Sundarbans (mosaic)
Mangroves @ Zambezi Delta

Approximately 12,000 km² area
The waters are estuarine and brackish to around 50 km inland.
Mangrove height up to 35 m
Tree diameter up to 60 cm

TDX HH-pol. Mangrove Canopy Height

Polarization: HH
Acquisition data: 2011/10/14
Acquisition mode: Descending
Vertical wavenumber: -0.086 rad/m
Height of Ambiguity: -80.91 m
System Bandwidth: 100 MHz
Mangroves @ Zambezi Delta

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- Vertical wavenumber: -0.086 rad/m
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- System Bandwidth: 100 MHz
Validations @ Zambezi Delta

- Date: 2014/05/05 – 2014/05/16
- Spatial resolution: 1 m X 1 m

- Date: September 2013
- 7 m Radius Subplots
- 0.52 ha Plot (72 m X 72 m)
- Total 40 plots / 9027 trees
- Species / Height / DBH

- Date: 2013/01/07
- WorldView-2 Satellite
- Spatial Resolution = ~0.6 m
- DSM Resolution = ~0.8 m
The World Largest Mangrove Forest; Sundarbans

- Sundarbans is located at the mouth of the Ganges-Brahmaputra Delta in India and Bangladesh.
- Mangrove height: up to ~20 m

- 26 TanDEM-X data sets were used for mosaicking
- January 22, 2011 to January 1, 2013 (13 different dates)
- Height of ambiguity: 29.88 m ~ 49.88 m
- Tide gauge information (-1.94 m ~ 1.56 m)
  -> Individual inversion results were fixed to mean sea level using tide information
The World Largest Mangrove Forest; Sundarbans

India

Bangladesh
The World Largest Mangrove Forest; Sundarbans

India

Bangladesh

WorldView2

TanDEM-X

Scale (km)

Height [m]

0

1 km
Mangroves @ Sundarbans

- Subjective definitions
  - TanDEM-X Canopy Height Map
  - Country
  - Species
  - Latitude
  - Geomorphology
  - Salinity
  - Soil map
  - < 5 m: ~80% India part / ~18% Bangladesh part

- Validation data
- Height-Biomass Allometric Equation

- 3-D Height map for field survey plan

Validation

- Field Survey

Sample: 12 m² / Bins: 0.5 m

Country: India: 2136.05 km²
Bangladesh: 4464.31 km²

Canopy Height Distribution

\[ R^2 = 0.830 \]

RMSE = 0.838 m
Andros Island, Bahamas

\[ R^2 = 0.709 \]
\[ \text{RMSE} = 2.424 \text{ m} \]

\(~200 \text{ km} \times ~100 \text{ km}\)
Summary

**TanDEM-X & Pol-InSAR technique**

- The first country-scale mangrove canopy height map at 12-m spatial resolution with an improved accuracy
- Great possibility for global mangrove height map from the global TanDEM-X DEM acquisition.
- Forest applications for flat terrain areas (e.g. wetland, inland and coastal deltas ...
Question?