Assessment of tropical forest biomass: A challenging objective for the Biomass mission

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Why are tropical data most uncertain and so important?

1. Tropical biomass = 350-680 billion tons
2. Uncertain due to biodiversity and poorly coordinated/sparse measurements

Global Forest Carbon Budget is most uncertain in the Tropics

<table>
<thead>
<tr>
<th>Carbon sink/source</th>
<th>Giga tons Carbon per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boreal</td>
<td>0.5±0.1</td>
</tr>
<tr>
<td>Temperate</td>
<td>0.7±0.1</td>
</tr>
<tr>
<td>Tropical Intact</td>
<td>1.0±0.5</td>
</tr>
<tr>
<td>Tropical regrowth</td>
<td>1.7±0.5</td>
</tr>
<tr>
<td>Tropical deforestation</td>
<td>-2.8±0.5</td>
</tr>
</tbody>
</table>

Pan et al., 2011
Biomass product requirements

**Forest biomass**
- Above-ground biomass (tons / hectare)
- 200 m resolution
- Accuracy of 20%, or 10 t ha$^{-1}$ for AGB < 50 t ha$^{-1}$

**Forest height**
- Upper canopy height (meter)
- 200 m resolution
- Accuracy of 20-30%

**Disturbances**
- Areas of forest clearing (hectare)
- 50 m resolution
- 90% classification accuracy

• 1 map every 6 months for 4 years
• Global coverage for forested area
Tropical forest

- High values of above ground biomass $\rightarrow$ 500 t/ha
- High and dense canopy
- Complex structure: multi species, multi age classes
- Frequent cloud and rain
- Intact forest remains in terrain with topography
BIOMASS will deliver 3 independent types of information for biomass

**PolSAR**
(SAR Polarimetry)

**PolInSAR**
(Polarimetric SAR Interferometry)

**TomoSAR**
(SAR Tomography)
Effects to be understood and accounted for

- Forest structure
- Tree physiology
- Topography
- Soil moisture
- Rain, winds
Why P-band SAR measurements are sensitive to biomass?

Amount of free water in woody elements

Dry biomass

Wet biomass: Wood + free water + bound water

Dry biomass: Wood + Protoplasmic (bound) water (moisture content ~12%)
Dry biomass

Ecerex database (French Guiana)

Water content

MEASURED WEIGHT OF DRY BIOMASS
FIT FUNCTION FOR DRY BIOMASS
MEASURED WEIGHT OF WATER CONTENT
FIT FUNCTION FOR WATER CONTENT

MEASURED WEIGHT OF WET BIOMASS (in tons)

MEASURED WEIGHT OF DRY BIOMASS (in tons)
POLSAR: Physical background

Radar scattering and attenuation are a function of the number, dimension, distribution, dielectric constant of scatterers interacting with the radar waves: radar backscatter intensity increases with biomass until attenuation becomes significant.
Data Source:
Uganda: ALOS-PALSAR data (Mitchard et al., 2009)
Cameroon: ALOS PALSAR data (Mermoz et al., 2013)
Costa Rica: AirSAR over La Selva forest (Antonarakis et al., 2011)
French Guiana: TropiSAR data (Dubois-Fernandez et al., 2012)
Effect of tree physiology: diurnal cycle of the backscatter

TropiScat Experiment
P-band radar measurement from 55m flux tower in French Guiana during long periods since Dec 2011

Linked to diurnal variation of dielectric constant related to transpiration and xylem sap flow

Diurnal variation: ± 0.5 dB requires observation at same time of the day
Dielectric constant of woody elements

McDonald et al., 2002
Variation in intensity around 6am and 6pm

6:00 ± 1h  18:00 ± 1h

Loss of water by transpiration
Upward water flow in xylem
Diurnal cycle of the P-band backscatter

Radar detects variation of centre of mass during daytime

Tree top height

Variation of the Centre of Mass detected by TropiSAR

Orbit for 6am equator crossing time
Diurnal cycle of the P-band backscatter

Radar detects variation of centre of mass during daytime

Tree top height

6 a.m. 6 p.m.

Variation of the Centre of Mass detected by TropiSAR

Leaf Water Potential and Sap flow simulated by the SPA model (Uni of Edinburgh).

The timing and direction of the centre of mass detected by the radar match the movement of water within the vegetation.
Visible topographic effect over dense forest
Based on the TropiSAR data analysis and on electromagnetic simulations, a **new indicator** $t^0$ has been developed, which includes 2 types of topographic corrections:

1) Topographic correction of the reflection symmetry, based on polarimetric property of the coherency matrix $[T]$

2) Topographic correction of the backscatter angular variations, which depend on the dominant scattering mechanisms

Villard & Le Toan, 2014
Topographic corrections 1

1) Topographic correction of the reflection symmetry, based on polarimetric property of the coherency matrix $[T]$

\[
\begin{align*}
\text{Scattering matrix:} \\
[S] & \\
\rightarrow [T] & \\
\rightarrow \text{POA} & \\
\rightarrow [T]^c & \\
\rightarrow \text{DEM (SRTM)} &
\end{align*}
\]

\[
\begin{align*}
\text{Compensated coherency matrix:} \\
[T]^c &= [U] \cdot [T] \cdot [U]^t \\
[U] &= \begin{bmatrix} 
1 & 0 & 0 \\
0 & \cos 2\widehat{\text{POA}} & \sin 2\widehat{\text{POA}} \\
0 & -\sin 2\widehat{\text{POA}} & \cos 2\widehat{\text{POA}} 
\end{bmatrix}
\end{align*}
\]

\[
\begin{align*}
\text{Polarisation Orientation Angle:} \\
\tan 4\widehat{\text{POA}} &= \frac{-2\Re\left(\langle(S_{hh} - S_{vv}) \cdot S_{hv}^*\rangle\right)}{4\langle|S_{hv}|^2\rangle - \langle|S_{hh} - S_{vv}|^2\rangle}
\end{align*}
\]

\[
\begin{align*}
\text{Compensated coherency matrix, normalised for angular variation:} \\
[T]^c &= [U] \cdot [T] \cdot [U]^t
\end{align*}
\]
Topographic correction of the backscatter angular variations, which depend on the dominant scattering mechanisms (Villard et al., 2011: *double bounce is significant for hilly terrain*).

$t^0$ is derived using the coefficients $t^c_{ij}$ of the corrected coherency matrix $[T]^c$:

$$t^0 = \left\langle \frac{1}{N^0} (t^c_{11} + t^c_{33}) \right\rangle$$

with the normalisation factor:

$$N^0 = \frac{\cos^2 \theta_i \cdot \cos \psi_n^p}{\cos \psi_g} \cdot A_s$$

\[
\theta_i = a \cos (\hat{n} \cdot (-)\hat{k}_i), \quad \psi_g = a \cos (\hat{v}_i \cdot (-)\hat{n}), \quad \psi_n^p = a \cos (\hat{z} \cdot \hat{n}^p), \quad \hat{n}^p = \hat{n} - (\hat{n} \cdot \hat{h}_i)\hat{h}_i
\]

the unitary normal vector to the surface.

the unitary vectors defining the incident linear (vertical/horizontal) polarisation basis and
In tropical forest, importance to remove topography effect

Correction for topographic effects and scattering mechanisms using polarimetry and a DEM.

Tropical forest, French Guiana

Backscatter at single polarisation (HV) in dB

\[ \rho = 0.16 \]

Polarimetric biomass indicator (dB)

\[ \rho = 0.68 \]
PolInSAR provides an estimate of height

- Interferometry provides height information
- The measured height depends on polarisation
- PolInSAR retrieves canopy height using models
PolInSAR requires high coherence

1. Small variation around 6:00 ±15min
2. Larger variation around 18:00 ±15min
3. Wind effect during the day to be avoided
Seasonal variation: coherence is higher in the dry season, giving better height estimates.

**TropiScatt** experiment:
- Tower-based P-band tomographic measurements.
- Measurements every 15 minutes.
- Started December 2011, still running.
Terrain topography also impacts forest height estimates from Pol-InSAR:

> The intercepted forest volume by the radar resolution is strongly impacted by the layover effect.
> Assuming a given constant forest height, the various topography configurations shown above lead to different retrieved height from Pol-InSAR $h_P$ (under/over-estimated regarding $h_c$).

$$h_c = h_{Pol-InSAR} \cdot \left[ 1 - \frac{\tan \left( \arccos \left( \hat{z} \cdot \hat{n}_P \right) \right)}{\tan \theta_T} \right] \quad \text{with: } \hat{n}_P = \hat{n} - (\hat{n} \cdot \hat{h}_i) \hat{h}_i$$
The compensated height is better related to biomass. 

\[ r = 0.66 \] 

\[ \rho = 0.19 \]
Tomography to understand scattering mechanisms

Boreal forest

Tropical forest

TomoSAR:

1. Provides a 3D reconstruction of forest backscatter.
2. Allows an interpretation of scattering processes
3. Gives guidance to the PolSAR and PolInSAR retrieval algorithms
P-band TomoSAR provides high accuracy biomass map

Paracou, tropical forest
112 in-situ plots: 100 m x 100 m

AGB map at 50 m, by tomography

BIOMASS tomographic phase:
> 4 baselines for 1 strip map
1 year operation
A global coverage
Combining POLSAR and Pol-InSAR improves biomass estimates

Algorithm used at CESBIO

- Coherency matrix \([T]\)
- Pol-InSAR coherences
  - Filtering, angular normalization
  - Geometrical and coherence optimization
- SAR data

AGB indicators from SAR

- Backscattering coefficients \(\gamma^0, t^0\)
- Pol-InSAR height \(h^C\)
- DEM [model + calibration from test plots]

AGB from weighted Bayes estimate

AGB from Combined Bayes estimate

AGB from Bayes estimate from \(h^C\)

DEM corrections
Combining estimators improves performance in tropical forests

Paracou, French Guiana, 6 MHz data; in situ biomass = 260-430 ton/ha

Thuy Le Toan, CESBIO

POLSAR

POL-InSAR

POLSAR & POL-InSAR

TomoSAR

\begin{align*}
&\text{RMSE} = \frac{\text{estimated} - \text{in situ}}{\text{mean biomass}}
\end{align*}

- $r = 0.52$, RMSE = 17%
- $r = 0.49$, RMSE = 15%
- $r = 0.73$, RMSE = 12.5%
- $r = 0.83$, RMSE = 10%
For biomass and height retrieval in tropical forests, factors that can effect the relationship between the SAR measurement and biomass must be understood and accounted for.

During dry period, for 6 am local time, with adequate topographic correction, and geometric projection, the expected relative RMSE is < 20% for biomass up to 500 t/ha

Combination of POLSAR and POLInSAR improves biomass retrieval

TomoSAR is the best tool for biomass retrieval. The performance during rainy period remains to be assessed

There are openings to explore the links of P-band SAR measurements and forest physiology