PolInSAR Height Retrieval Method based on Electromagnetic Forward Meta-Model initiated with TomoSAR Estimates: Applications on TropiSAR Data and Prospects for Biomass mission

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Context:

P-band Biomass mission retrieval algorithm for forest height and forest Above Ground Biomass (AGB)
- Retrieval methods developed during Phase A
- Limitations & prospects of improvements

Retrieval methods based on Forward Electromagnetic (EM) model:
- Highlights on MIPERS (ex of EM coherent model based on forest description)
- Possible use for retrieval?

Development of Forward Meta/Surrogate Models:
- Motivations
- Reducing the input space
- Generating an interpolated Surface Response

Applications to TropiSAR data, interest of TomoSAR DEM estimates
- Parametrization (constrains) of the inverse problem
- Results on height retrieval
Retrieval methods developed during Phase A for tropical dense forests

**PolSAR** (SAR Polarimetry)

**PolInSAR** (Polarimetric SAR Interferometry)

**TomoSAR** (SAR Tomography)
Retrieval methods developed during Phase A for tropical dense forests

- P band SAR data
- Coherency matrix [T]
- Coherence optimization, geometrical factor
- Filtering, angular normalization
- Pol-InSAR coherences
- Backscattering coefficients ($\gamma^0$, $\iota^0$)
- DEM
- Pol-InSAR height ($h^c$)
- Weighted Bayes model based on calibration from test plots
- Combined Bayes estimates with confidence level
- Test plots from in-situ estimates
- Test plots from TomoSAR estimates
- AGB indicators from SAR
- AGB estimates
Retrieval methods developed during Phase A for tropical dense forests

TropiSAR campaign* & the challenge of tropical dense forest P-band SAR

The Paracou test site (www.ecofog.gf)

~85 ha of plots (250-450 t/ha)


ESA-CNES fundings, managed by ONERA during Aug-Sept 2009 PolSAR / PolInSAR & TomoSAR acquisitions
Retrieval methods developed during Phase A for tropical dense forests

Insights from TropiSAR

Advanced methods required to account for topography effects (given the reduced sensitivity of I0/hP indicators to AGB)
Retrieval methods developed during Phase A for tropical dense forests

**PolSAR indicators**

- \( \gamma_{hw}^0 \) [dB]
- \( \rho^0 \) [dB]

**Pol-inSAR indicators**

- \( h^P \) [m]
- \( h^C \) [m]

- L. Villard, T. Le Toan. ‘Relating P-band PolSAR intensity to Above Ground Biomass of TropiCal Dense Forest: g0 or t0? IEEE JSTAR, Dec 2014

- ** L. Villard, P. Dubois Fernandez, T. Le Toan. ‘Specific correction of topography Effects on PolInSAR height at P-badnover Tropical Forest, I proc POLInSAR 2013

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**1st BIOMASS SCIENCE WORKSHOP**

27–30 January 2015 | ESA–ESRIN | Frascati (Rome), Italy
Retrieval methods developed during Phase A for tropical dense forests

Specific corrections of ground slopes enable to recover the sensitivity of intensity/PolInSAR indicators to AGB

However, the saturation phenomenon remains an issue.
Retrieval methods developed during Phase A for tropical dense forests

Bayesian estimator to combine intensity and PolinSAR indicators
Retrieval methods developed during Phase A for tropical dense forests

Bayesian estimator to combine intensity and PolinSAR indicators
Retrieval methods developed during Phase A for tropical dense forests

Results much improved (within 20% specification) but test plots calibration are still required

\[ y^0_{hv}[dB], t^0_{dB}, h[m] = a_1 \cdot \log_{10}(AGB[t/ha]) + a_0 \]
Retrieval methods developed during Phase A for tropical dense forests

Given the limitations of the retrieval method based on the combined power laws (intensity/PolinSAR):
- test plots required (in-situ network, LiDAR, TomoSAR estimates)
- partial use of SAR vector
- not easily adaptable to ancillary data

are EM Forward model adapted for retrieval?
Discrete geometrical description based on canonical shapes (cylinders, ellipsoids) statistically distributed (Monte-Carlo process)

2 possible descriptions for tropical forests:
   a) based on layers
   b) based on tree architecture models (adapted from TROLL*)

Underlying topography modeled with 3D triangular facets

*J. Chave et al, ‘Study of structural, successional and spatial patterns in tropical rain forests using TROLL, a spatially explicit forest model’, Ecological Modelling, 1999.
Coherent modeling based on the DBWA (Distorted Born Wave Approximation) and scattering matrices of canonical shapes.

Accounts for several contributions:

- single scattering mechanisms from vegetation scatterers and the ground
- multiple scattering mechanisms resulting from coupling effects between vegetation and ground
EM modeling with MIPERS
(Multistatic Interferometric & Polarimetric model for Remote Sensing)

**Coherent summation** to generate Radar observables:
Polarimetric & Interferometric SAR measurements + non measurable quantities related to individual contributions (branches, trunks, ground and for each scattering mechanism)

\[
E_s(\vec{r}_R; \vec{r}_T) = \left( \sum_P \right) e^{-j\varphi_P^{ds}} [t_p(\hat{k}_s)] \cdot [S_p(\hat{k}_i, \hat{k}_s)]
\]

\[
\frac{d(E_v)}{dr} = j(k_0 - \frac{\sigma_w}{2})(E_v) - j \frac{\sigma_{\psi n}}{2} (E_h)
\]

\[
\frac{d(E_h)}{dr} = -j \frac{\sigma_{\psi n}}{2} (E_v) + j(k_0 - \frac{\sigma_{\psi n}}{2}) (E_h)
\]

with: \( \sigma_{qp}(\theta, \phi) = \frac{4 \pi n_0}{k_0} \langle \text{Im}(S_{qp}(\theta, \phi)) \rangle_{p,o,s} \)
EM modeling with MIPERS
(Multistatic Interferometric & Polarimetric model for Remote Sensing)

EM calculations

Coherent summation to generate Radar observables:
Polarimetric & Interferometric SAR measurements + non measurable quantities related to individual contributions (branches, trunks, ground and for each scattering mechanism)
Possible use of EM models for retrieval?

Main advantages of EM forward models:

- Simulations of full SAR observation vector (POLSAR, POLinSAR, TomoSAR at pixel scale (slc) with speckle and SD
- Change of configuration (e.g. incidence angle)
- Ancillary data can be easily included
Retrieval method based on comparison between predictions (forward model) and observations (SAR data)

Possible use of EM models for retrieval?

Test/guest vector (specific stage of forest stand model)

Parametrization (Allometry + ancillary data (LiDAR, Optical))

MIPERS (forward model)

Observations (PolSAR/PolInSAR)

Cost - Likelihood Function (weighted sum, based on observed/predicted uncertainties)

Optimal solution (w.r.t convergence criteria)
Possible use of EM models for retrieval?

Retrieval method based on comparison between predictions (forward model) and observations (SAR data)

Main limitations:
- extensive set of input parameters
- computing time

Ex of 1ha forest stand
50e3 vege scatterers/ha with geometrical & dielectric features, + ground surface mesh
2min CPU(qdcore 4*8 GHz)
Retrieval method based on comparison between predictions (forward model) and observations (SAR data)

Main limitations:
- extensive set of input parameters
- computing time

→ interest in developing surrogate models:
- simplified parametrization
- faster
- reliable: estimates as close as possible to complete model

Possible use of EM models for retrieval?
Surrogate model development

1) Reducing the set of input parameters

\[ AGB [t/ha] \quad \xrightarrow{(\rho)} \quad h [m] \quad \xrightarrow{(2)} \quad DBH [cm] \quad \xrightarrow{(3)} \quad BA [m^2] \]

\[ \xrightarrow{N_t [ha^{-1}]} \quad r_t [m] \quad \xrightarrow{(h_t/h)} \quad AGB_c [t/ha] \quad AGB_t [t/ha] \]

* Use of Forest Growth Descriptive Model (FGDM*)

1) Reducing the set of input parameters

\[ AGB_{t/ha} \]
\[ h[m] \]
\[ DBH[cm] \]
\[ BA[m^2] \]
\[ N_t[ha^{-1}] \]
\[ r_t[m] \]
\[ AGB_{c}[t/ha] \]
\[ AGB_t[t/ha] \]

> Use of Digital Terrain Model (under vegetation, as future Biomass product after 1rst year of P-band TomoSAR global acquisitions)
2) Interpolated 'surface' (Xd) response

Bench of interpolating technique: GLS, Neural N., SVR and Kriging:
→ robustness and stability w.r.t to statistical dispersion
2) Interpolated 'surface' (Xd) response

Minimize: $\text{Var}[\hat{Z}(\mathbf{X}) - Z(\mathbf{X})] = \sum_{i=1}^{N} \sum_{j=1}^{N} \lambda_i \lambda_j \text{Cov}[Z(\mathbf{X}_i), Z(\mathbf{X}_j)]$

$-2 \sum_{i=1}^{N} \lambda_i \text{Cov}[Z(\mathbf{X}_i), Z(\mathbf{X})] + \text{Var}[Z(\mathbf{X})]$

Subject to: $f_l(\mathbf{X}) = \sum_{i=1}^{N} \lambda_i f_l(\mathbf{X}_i) \quad l = 1, 2, \ldots, M$
Application to TropiSAR data

Parametrization of the inverse problem

- Test vector: initiated with hC (Pol-InSAR corrected height)
- FGDM: allometric model relations (mainly driven by AGB/BA/h)
- Constrained values for VWC (Vegetation Water Content), Soil Moisture
- **TomoSAR estimate of the DTM**
- Cost function: based on obs/sim coherences at 12.5*25 m pixels (cf. Biomass)

**Surface ground mesh extrapolated from TomoSAR DTM estimate** (*D. Ho Tong Minh et al, [2013, 15]*)
Application to TropiSAR data

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Application to TropiSAR data

Parametrization of the inverse problem

- Test vector: initiated with $h_C$ (Pol-InSAR corrected height)
- FGDM: allometric model relations (mainly driven by AGB/BA/h)
- Constrained values for VWC (Vegetation Water Content), Soil Moisture
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Application to TropiSAR data

- Test vector: initiated with hC (Pol-InSAR corrected height)
- FGDM: allometric model relations (mainly driven by AGB/BA/h)
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- TomoSAR estimate of the DTM
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Cross-comparison with LiDAR heights
(gray: original PolInSAR hC
Red: level 1 FGDM)

\[ R = 0.75 \]
\[ \text{RMSE} = 6.54 \text{m} \]
Application to TropiSAR data

> Test vector: initiated with hC (Pol-InSAR corrected height)

> FGDM: allometric model relations (mainly driven by AGB/BA/h)

> Constrained values for VWC (Vegetation Water Content), Soil Moisture

> TomoSAR estimate of the DTM

> Cost function: based on obs/sim coherences at 12.5*25 m pixels (cf. Biomass)

Cross-comparison with LiDAR heights
(gray: original PolInSAR hC
blue: level 2 FGDM)

$R = 0.75$
$\text{RMSE} = 5.8\text{m}$
Application to TropiSAR data

Parametrization of the inverse problem

- Test vector: initiated with hC (Pol-InSAR corrected height)
- FGDM: allometric model relations (mainly driven by AGB/BA/h)
- Constrained values for VWC (Vegetation Water Content), Soil Moisture
- TomoSAR estimate of the DTM
- Cost function: based on obs/sim coherences at 12.5*25 m pixels (cf. Biomass)

Cross-comparison with LiDAR heights
(gray: original PolInSAR hC, green: level 3 FGDM)

$R = 0.87$, $RMSE = 4.01$ m
Conclusions

- **First results** demonstrating the use of forward model for retrieval, based on TomoSAR DTM estimates and Forest Growth Descriptive Model - FGDM) + guest vector from PolInSAR height

- **Main advantage of the method**: more complete use of SAR observation vector:
  - TomoSAR DTM
  - Account for physical information embedded in statistical variability (speckle) and avoid the issue of dealing with spatial estimator

- **On-going work**:
  - Allometric relations still required (FGDM calibration)...possible use of TomoSAR estimates of vegetation structure (robust enough to temporal variations)
  - Developing the surface response (Kriging) accounted for the full [S] matrix (not only complex coherences)
  - Relax constrains (Including VWC, WC)
  - Much can be also expected from future computing efficiency
Thank you for your attention

& thank you for your questions...