Polarimetric SAR tomography of tropical forests using P-Band TropiSAR data

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Objectives

- Global objectives: Characterization of tropical forests
  - Tree height & biomass
  - Robustness assessment

- First year objectives:
  - Implement classical tomographic approaches
  - Single-pol (SP) and full-pol (FP) configurations
  - Estimate tree height

- Second year:
  - Estimate biomass or biomass-related quantities (extinction)
  - Compare to POL-inSAR
  - Test baseline configurations

Work done up to now

- POLTOM data obtained at the end of August 2010
- Classical tomographic approaches implemented, SP and FP versions
- Very fast tree height estimation: hybrid HR methods
- Tries at L band
- Comparison with POL-inSAR under investigation
Tomography basics

Acquisition geometry

MB-PollInSAR: Polarimetric tomography

- Localize scatterers in z direction & extract their physical features
- Nominal resolution $\delta_h \propto \frac{1}{L_{tomo}}$, ambiguity height $\Delta_h \propto \frac{1}{ds}$
Tomography basics

General signal model

\[ y = A(\theta)x + n \in \mathbb{C}^m \]

- \( x \in \mathbb{C}^d \): source (reflected) signals (\( d \) elements)
- \( m \times d \) steering matrix \( A(\theta) = [a(\theta_1), \ldots, a(\theta_d)] \)
- \( m \) - element steering vector, \( a(\theta_i) = a(z_i) = [1, \exp\{jk_z z_i\}, \exp\{jk_m z_i\}]^T \)

Focusing

- Continuous spectral estimators: Matched filter (Fourier), Capon ...
- Discrete ones: estimate the \( d \) sources
Power spectrum of various environments

- Natural environment (h-distributed scatterers): Continuous Spectrum

- Objects (h-localized scatterers): Discrete Spectrum

- Objects embedded in natural environment: Mixed-Spectrum
Classical spectral estimators for tomographic imaging

Nonparametric spectral estimators ⇒ Continuous spectrum

- Beamforming: $\hat{z} = \arg \max \{ a^H R a \}$
- Capon: $\hat{z} = \arg \max \{ \frac{1}{a^H R^{-1} a} \}$
  - $a$: steering vector
  - $R$: sampled data covariance matrix.
- Moderate resolution

Parametric spectral estimators ⇒ Discrete Spectrum

- E.g. Weighted Signal Subspace Fitting (WSF)
- $\hat{z} = \arg \min tr\{P_A^\perp \hat{E}_s W \hat{E}_s^H \}$
  - $P_A^\perp$: orthogonal projection matrix of steering matrix $A$.
  - $W$: weighting matrix
  - $E_s$: signal subspace
- High resolution

Lack of adaptation to the type of spectrum!
Unconditional MB-PolinSAR signal model

\[ y_u = \sum_{i=1}^{d} \sqrt{\sigma_i} x_{ui} \odot a(z_i) + n \]

- Valid for Distributed Scatterers with speckle affected responses (Ground)
- Stochastic source signal (white for each observation)

\[ x_i = \sqrt{\sigma_i} x_{ui} \quad \text{with} \quad x_{ui} \sim \mathcal{N}^m(0, C_i) \]

- \( C_i \) describes interferometric coherence
- \( y_u \sim \mathcal{N}^m(0, R_y) \)
- \( \sigma_i, z_i \) estimated from \( R_y \)
Conditional MB-PolinSAR signal model

\[ y_c = \sum_{i=1}^{d} \sqrt{\sigma_i} x_{ci} \odot a(z_i) + n \]

- Valid for coherent scatterers: (Double Bounce)
- \( x_i = \sqrt{\sigma_i} x_{ci} \) is deterministic (frozen) over \( N \) observations (looks)
- \( y_c \sim \mathcal{N}^m(Ax, \sigma_n^2 I) \)
- \( \sigma_i, z_i \) estimated from \( Ax \)
Hybrid SAR signal model

Mixture of coherent and distributed scattering contributions * (Sauer et al: 2007)

\[ y = y_c + y_u = \sum_{i=1}^{d_1} \sqrt{\sigma_i} x_{ci} a(z_i) + \sum_{i=1}^{d_2} \sqrt{\sigma_i} x_{ui} \otimes a(z_i) + n \]

Demonstration:

- Two-component hybrid source signal \( \mathbf{x}(l) = [\mathbf{x}_u(l), \mathbf{x}_c(l)] \)
  with \( \mathbf{R}_{xu} = \begin{bmatrix} \sigma_u & 0 \\ 0 & \sigma_u \end{bmatrix} \) and \( \mathbf{R}_{xc} = \begin{bmatrix} \sigma_c & \sigma_c \\ \sigma_c & \sigma_c \end{bmatrix} \)

- Source covariance matrix
  \[ \mathbf{R}_x = \mathbf{R}_{xu} + \mathbf{R}_{xc} = (\sigma_u + \sigma_c) \begin{bmatrix} 1 & \rho_{hd}^* \\ \rho_{hd} & 1 \end{bmatrix} \]

- Source correlation \( \rho_{hd} = \frac{1}{1 + \text{UCR}} \) with \( \text{UCR} = \frac{\sigma_u}{\sigma_c} \): uncoherent to coherent intensity ratio.
  \( \rho_{hd} \to 1, \mathbf{R}_x \to \text{singular} \)

- Hybrid model \( \Leftrightarrow \) correlated unconditional model
  \( \rho_{hd} \Leftrightarrow \) correlation of UMs.
Model adaptive WSF spectral estimator

Conventional estimators

- **MUSIC:** \( \hat{z} = \arg\min\{a^H E_n E_n^H a\} \rightarrow \) uncorrelated scatterers
- **Det-ML:** \( \hat{z} = \arg\max \text{tr}\{A(A^H A)^{-1} A^H \hat{R}_y\} \rightarrow \) coherent scatterers
- **Stoch-ML:** \( \hat{z} = \arg\min |P_A \hat{R}_y P_A + \hat{\sigma}^2 P_A^\perp| \rightarrow \) noncoherent scatterers
- \( E_n: \) noise subspace; \( P_A: \) projection matrix to the signal subspace; \( P_A^\perp: \) orthogonal projection matrix.

Model adaptive estimator: Weighted Subspace Fitting

\[ \hat{z}, \hat{T} = \arg\min \left\| E_s W^{1/2} - AT \right\|^2_F \]
Natural Environment: Hybrid tomographic method

Principle

- Hybrid: estimate both continuous and discrete spectral components
- Fast: Simple estimators, CAPON (canopy), WSF (ground and volume mass center)

- CAPON
  Backscattered power spectrum \( P(z) \)
- WSF (order=2)
  Ground topography \( z_g \)
  Phase center of the volume \( z_v \)
- Tree top height:
  \[ z_{\text{top}} = \{ z | P(z) = P(z_v) - 3\text{dB} \} \]

Easy extension of the proposed tomographic approach to the fully polarimetric case.
Test site: Paracou, French Guiana

- TropiSAR Campaign
- ONERA SETHI (P band)
- 6 tracks
- Resolution
  - Azimuth: $\delta_a = 1.245m$
  - Range: $\delta_r = 1m$
- Tomographic resolution $\delta_z \approx 20m$
Discrimination of bare soils and forested areas (MOS)
Forest profile estimation

Hybrid approach:
- **Tree Top**: black line
- **Ground**: gray line

- No profile post-processing (peaky aspect)
- Very similar FP and co-pol results
Ground topography and tree height estimation

- Shadowed regions should be masked out
ROI validation for P9 and P10 (logged plots)
ROI validation for P11 (Undisturbed forest) and P12 (logged plots)
Full-pol results

Worse than HH case, need for more sophisticated approaches

parametric tomography (2nd year)
First results on Nouragues

- No profile post-processing (peaky aspect)

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Conclusions

Tomographic results

- Excellent data quality at P band
- L band images for TOMSAR -Pol-inSAR ? ⇒ to be checked
- SP and FP tomograms provide very good profile description
- Topography can be handled (specific processing)
- Fast approach to estimate tree height and ground topo

Short term developments

- Tomogram filtering (peaky aspect) & shadow masking
- Systematic comparison to ground measurements (Paracou & Nouragues)

Mid term developments

- Full-pol parametric tomographic focusing (height and extinction)
- L band data processing & comparison to POL-inSAR