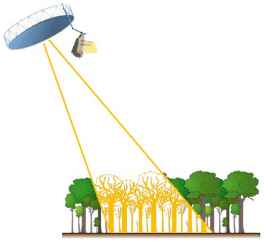

Apport des futures données SAR bande P multi-baselines : la mission BIOMASS

Ludovic Villard, Yassine Letaief, Dinh Ho Tong Minh(2), Thierry Koleck & Thuy Le Toan*

**today's presenter*

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Centre d'Etudes Spatiales de la BIOsphère
Toulouse – France

Outline

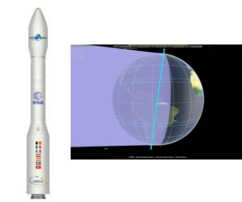
- Overview of the Biomass mission
  key studies & current research priorities
- Interest of P-band PolSAR data
  for dense forests remote sensing
- Capabilities of the multi-baseline configuration

Overview of the mission time-line

2009 | 2013 | 2016 | 2019 | 2021

Phase A | Phase B1/B2 | Phase C | Phase D | Phase E1/E2

Selection as the 7th Earth Explorer mission)



LAUNCH
(Vega)

Phases
A : Feasibility (of concepts)
B1 : Algorithm Requirement & Definition
(Product Definition & high level requirements)
B2,C : Prototype implementation
(Science and Developement)
D : Processor implementation & Testing
E : Exploitation

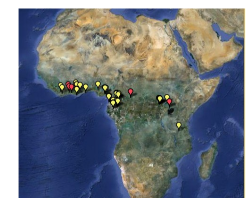
Feasibility of concepts

2009	2013	2016	2019	2021
Phase A	Phase B1/B2	Phase C	Phase D	Phase E1/E2

Phase A science activities: enrich the set of exp. data

Essentially driven by ESA/CNES airborne/ground based campaigns:

- BioSAR 1,2 & 3 (Airborne SAR / Sweden / 2007,8 & 2012)
- TropiSAR (Airborne SAR / French Guiana / 2009)
- TropiScat (Scatterometer / French Guiana / 2011-2014)
- AfriScat (Scatterometer / Ghana / 2015-2017)
- ***AfriSAR (Airborne SAR / Gabon / Jui,Feb 2016)***



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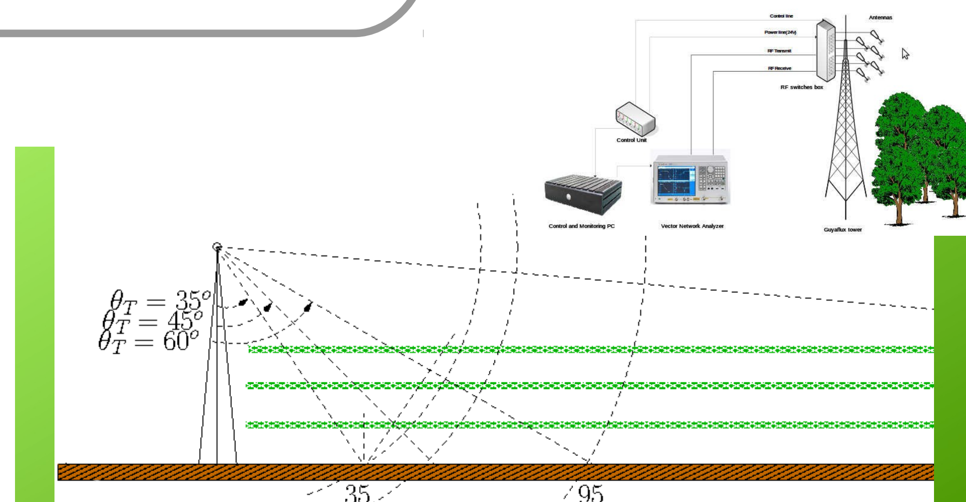
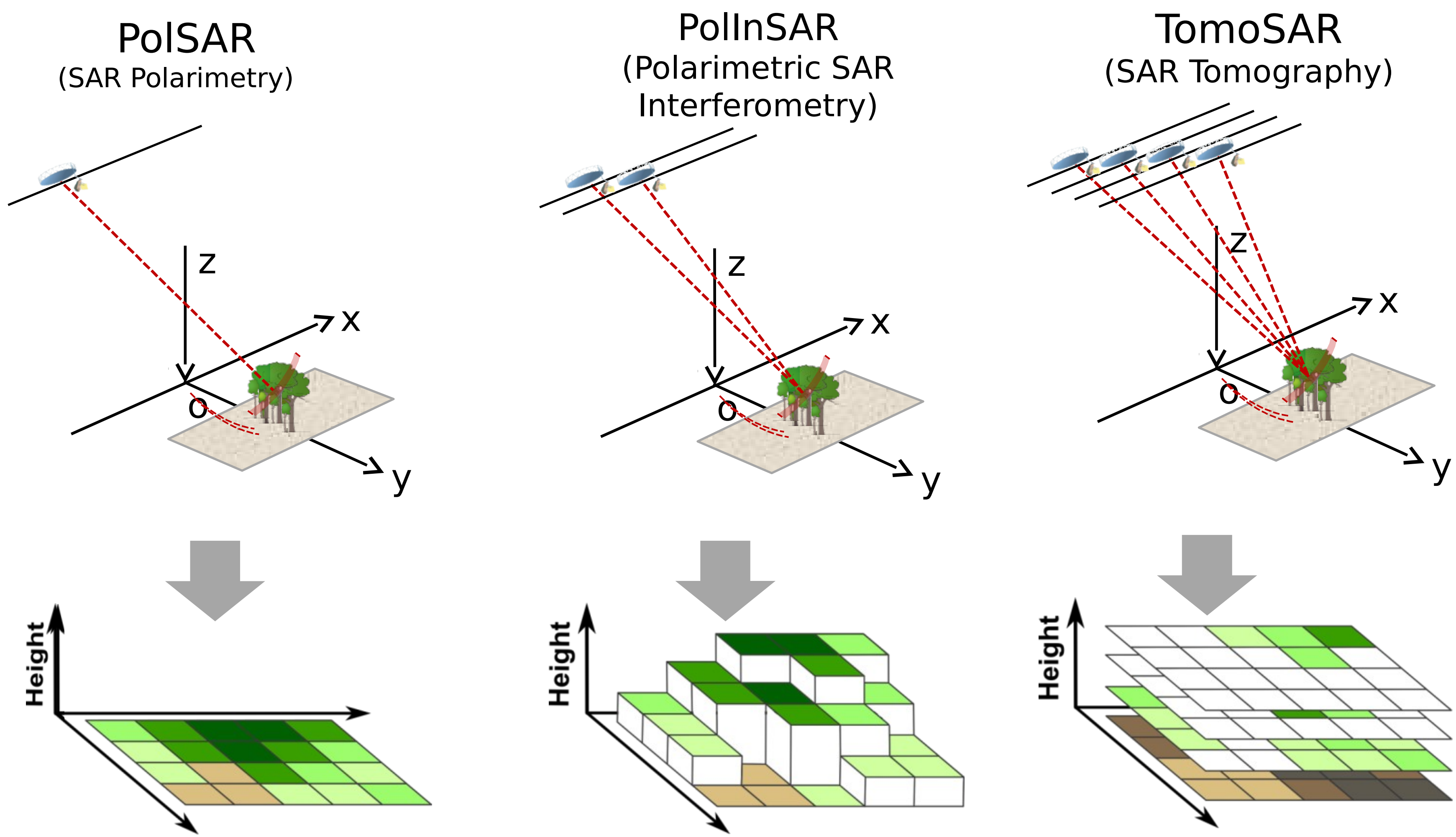


Feasibility of concepts

BIOMASS will be based on 3 types of P-band SAR acquisitions



BIOMASS products to answer its scientific objectives

Forest biomass

Above-ground biomass (tons/hectare)

- 200 m resolution
- 1 map every 6 months
- global coverage of forested areas
- accuracy of 20%, or 10 t ha^{-1} for biomass < 50 t ha^{-1}

Forest height

Upper canopy height (meter)

- 200 m resolution
- 1 map every 6 months
- global coverage of forested areas
- accuracy of 20-30%

Disturbances

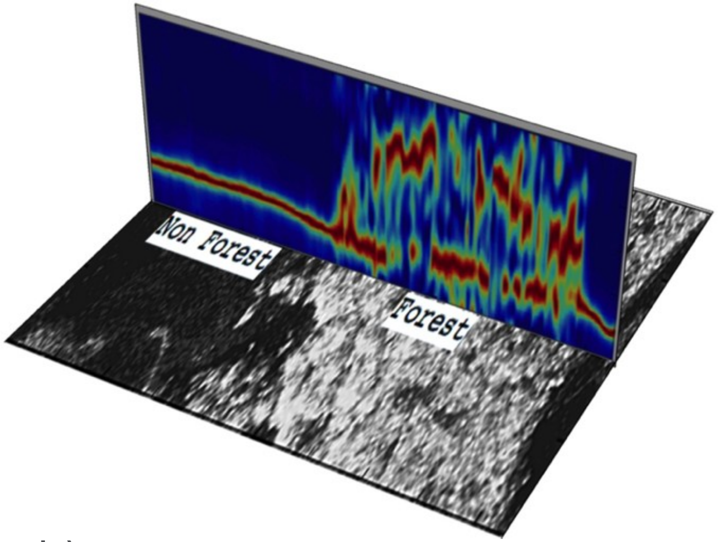
Areas of forest clearing (hectare)

- 60×50 m resolution
- 1 map every 6 months
- global coverage of forested areas
- 90% classification accuracy

BIOMASS products to answer its scientific objectives

Level 1:
1. Level-1a: SLCs
2. Level-1b: geocoded, multi-looked

Level 1.5:
3. SLC stacks (co registered and ionosphere corrected)
4. Tomographic Cubes

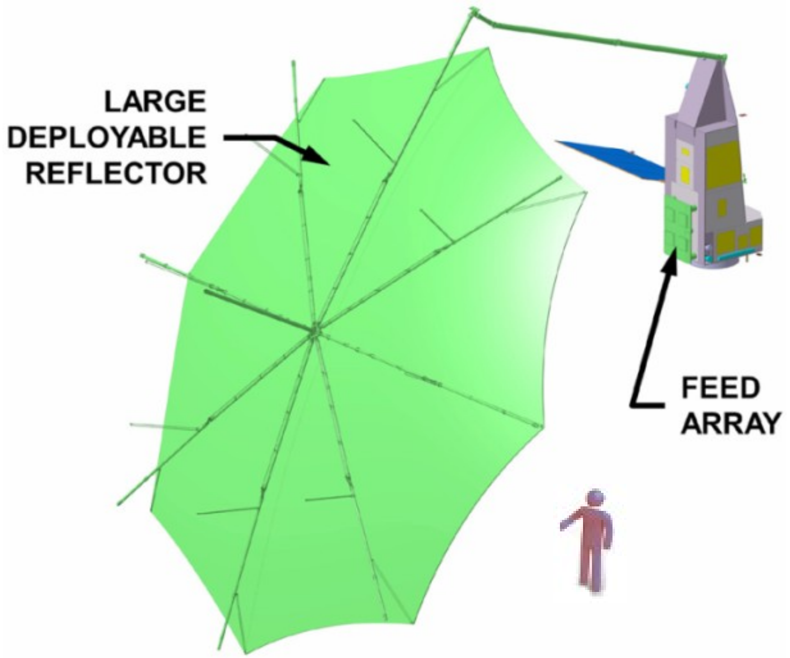


Level 2 (under definition)
5. Biomass based on a SLC triplet
6. Forest height based on a SLC triplet
7. Disturbance based on a SLC triplet

Level 3 (under definition)
8. Global Biomass Mosaic (every 7.2 month)
9. Global Forest height Mosaic (every 7.2 month)
10. Global Disturbance Mosaic (every 7.2 month)

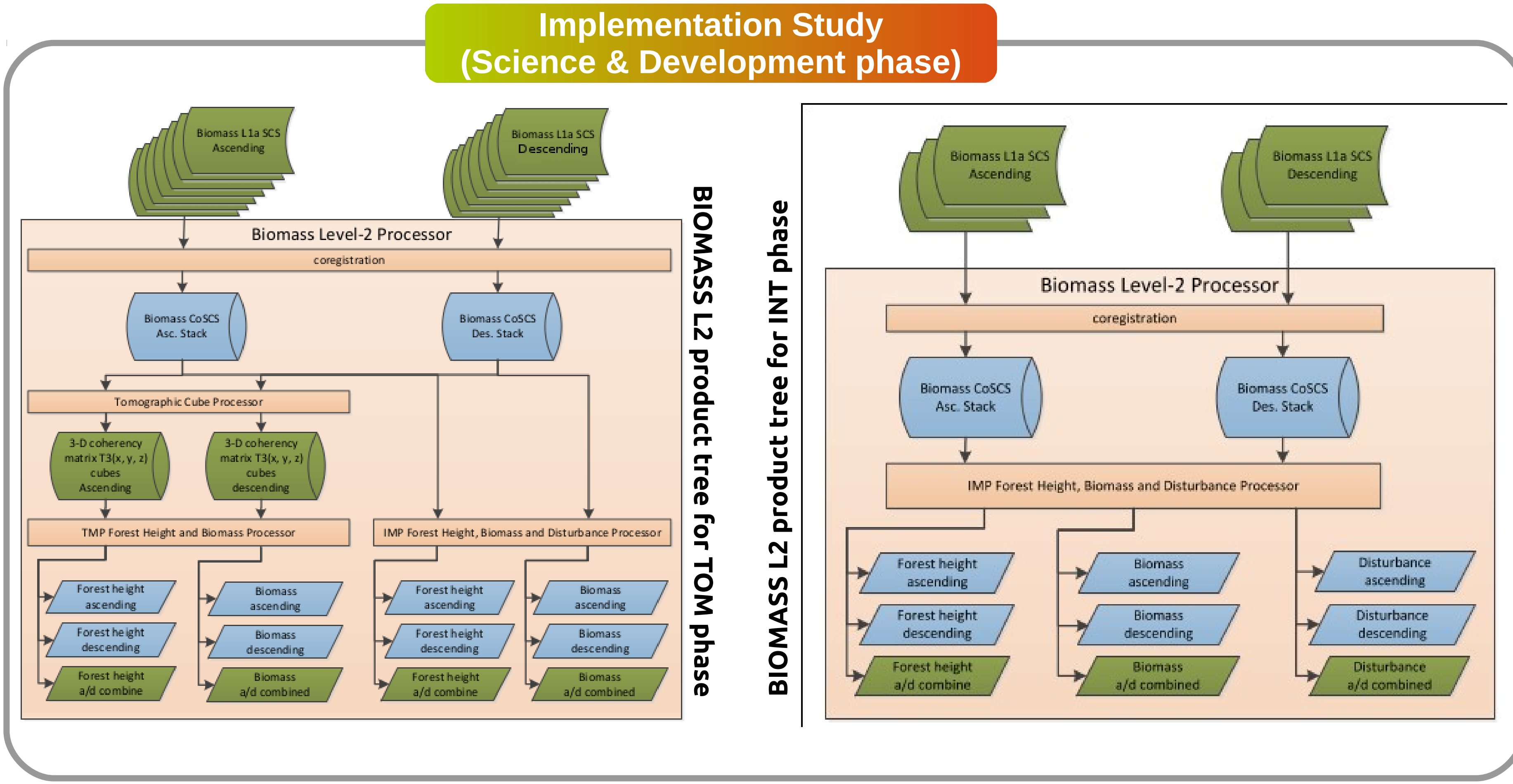
Biomass key facts

- ✓ Single satellite, 5 years lifetime
- ✓ P-band (435 MHz) Synthetic Aperture Radar (SAR)
- ✓ Full polarimetric (HH, HV, VV)
- ✓ 6 MHz bandwidth
- ✓ Level 1: 60 x 50 m^2 resolution
- ✓ Multi-pass interferometry with a 3 days repeat cycle
- ✓ Two mission phases: Tomography (14 monts), Interferometry (year 2-5)



Overview of the mission time-line

2009	2013	2016	2019	2021
Phase A	Phase B1/B2	Phase C	Phase D	Phase E1/E2



Overview of the mission time-line

2009 2013 2016 2019 2021

Phase A → Phase B1/B2 → Phase C → Phase D → Phase E1/E2

Implementation Study (Science & Development phase)
→ Research & Development

Key research priorities :

- Perturbations related to physical scattering
  - bio/geo-ecophysical changes
    (daily for ASC/DSC, seasonal between triplets)
  - Change of observation geometry (ASC/DSC)
- Algorithm Training&Validation strategy
  (for PolSAR, PolInSAR & TomoSAR based retrieval algorithms)
- Combination of PolSAR & PolInSAR
  (cf. fusion at AGB level or with PolInSAR height or other metrics)
- PolSAR & PolInSAR synergies with TomoSAR

Outline

- Overview of the Biomass mission
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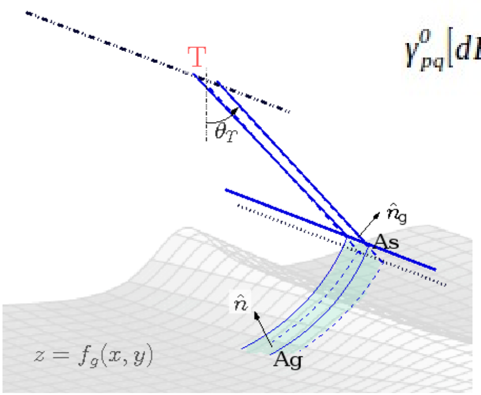
Specificity of the HV polarization

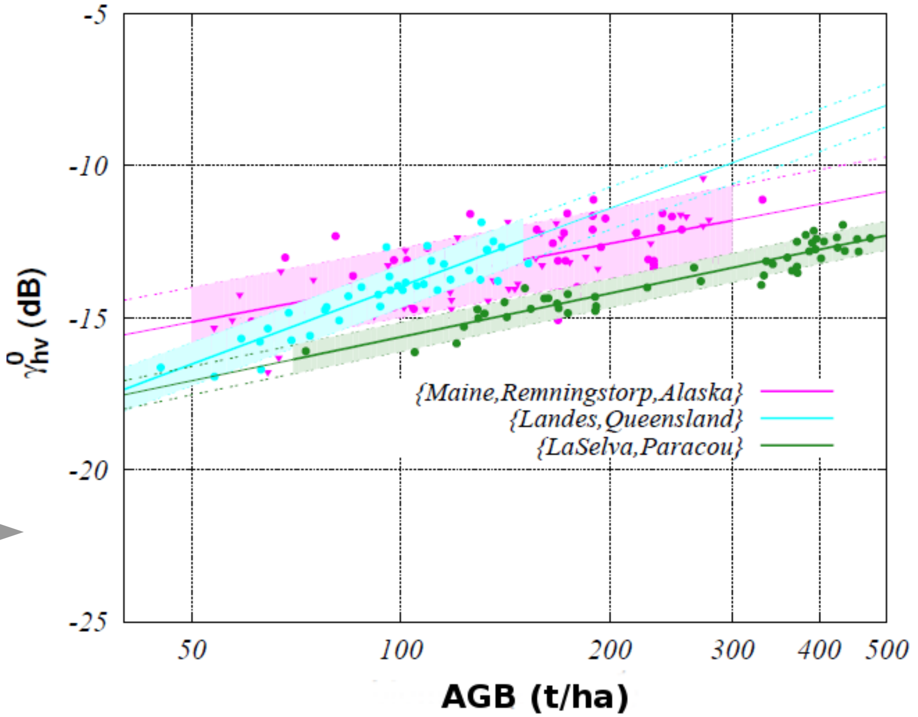
- How comes depolarization ?
- Resulting relation between
  cross-pol (HV) backscatter & vegetation biomass

Based on the normalization of the RCS*, specific backscatter coefficients can be derived :



$$\gamma^{0}_{pq}[dB] = 10.\log_{10}\left(\frac{\sigma_{pq}}{A_s}\tan(\theta_i)\right)$$

and related through power laws to forest Above Ground Biomass (AGB)

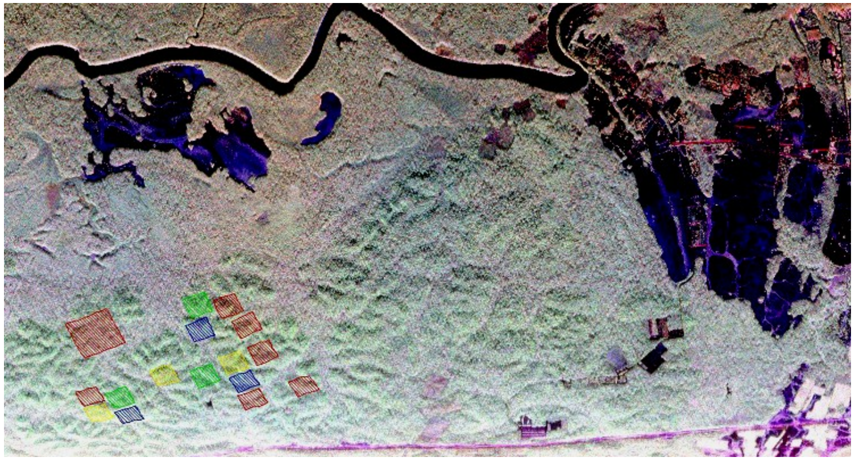


RCS: Radar Cross Section defined from the scattering matrix by: $\sigma_{pq} = 4\pi\left|S_{pq}\right|^2 = 4\pi R^2 \frac{P_s}{P_i}$ $[m^2]$ *with* R the radar-target distance, P_i is the incident power and P_s is the power scattered by the target.

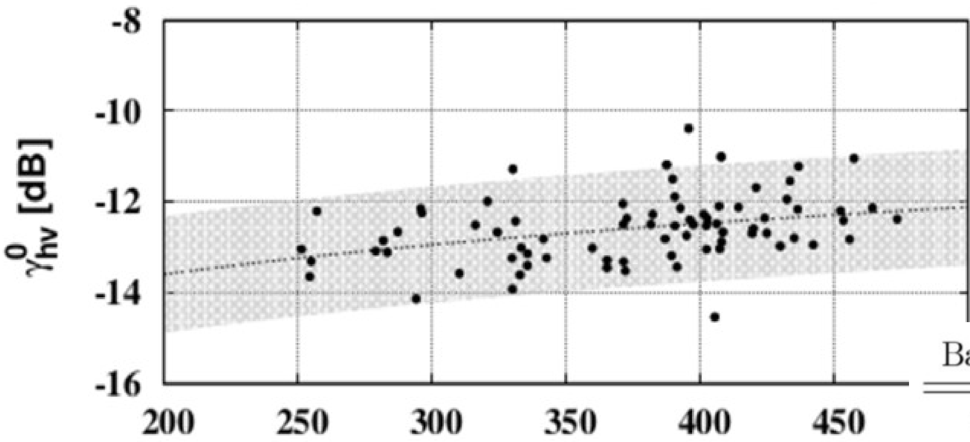
PolSAR based indicator to cope with the saturation issue

TropiSAR campaign* & the challenging case of tropical dense forests

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



Pauli RGB image on the Paracou test site



Regression parameters
(correlation, dispersion, slope and intercept with uncertanties)

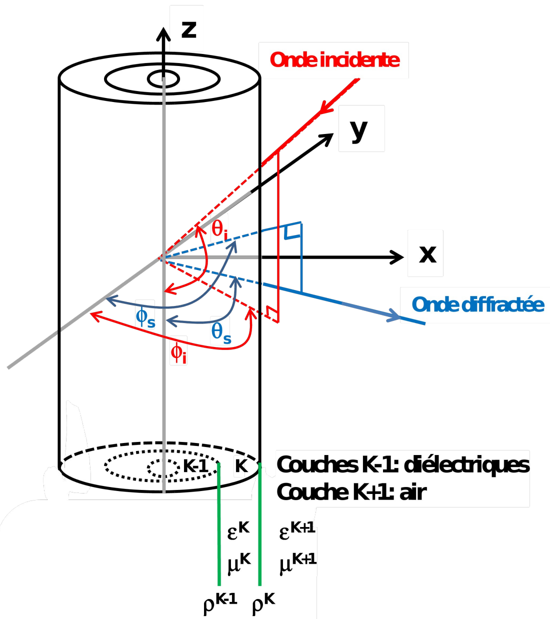
Backscatter	ρ	χ^2	a	b
$\gamma_{hv}^{0,FEA}$	0.19	52.64	2.33 ($\pm$1.808)	–18.64 ($\pm$4.646)
γ_{hv}^{0}	0.36	32.46	3.67 ($\pm$1.420)	–22.01 ($\pm$3.648)
t^0	0.68	15.17	6.00 ($\pm$0.971)	–25.96 ($\pm$2.494)

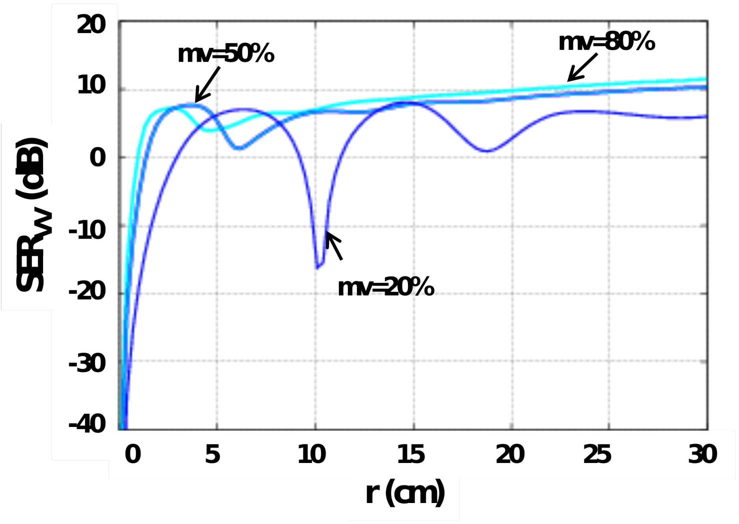
$$\gamma_{hv}^{0}[dB], t^{0}[dB], h[m] = a_1 \cdot \log_{10}(AGB[t/ha]) + a_0$$

Key features behind scattering mechanisms:

- Geometry (dimensions/orientations of scatterers in addition to bulk effects) with respect to the wavelength
- Dielectric constant of the material (frequency dependent, and mainly driven by water content)

Example of a dielectric cylinder:





PolSAR acquisition: beyond the HV backscatter

Based on the Pauli decomposition of the scattering matrix, the PolSAR information is commonly formulated with the coherency matric [T]

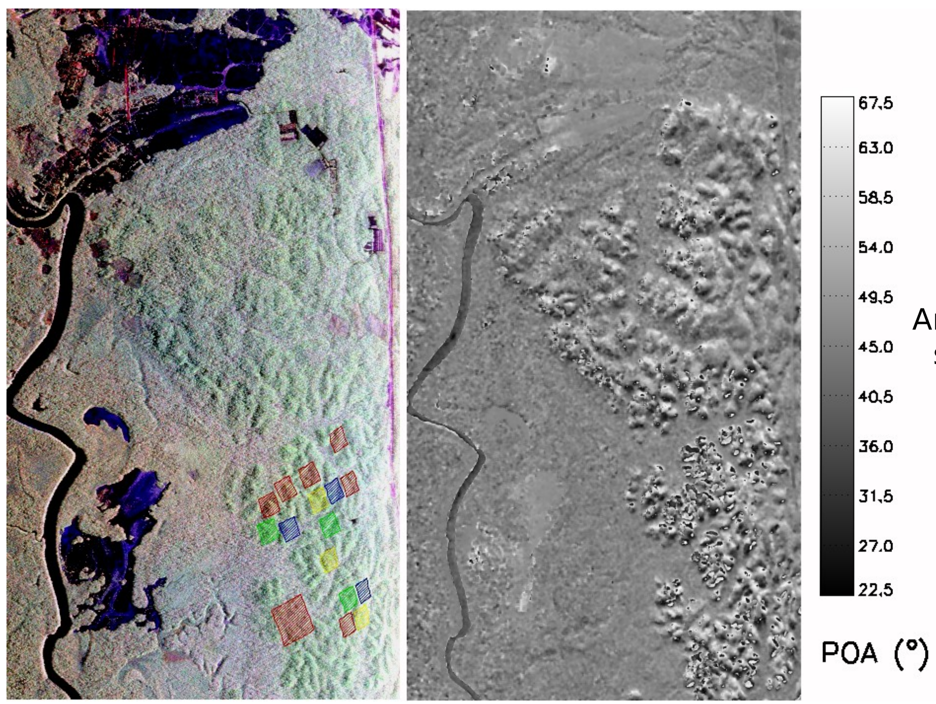
$$\{\varphi_P\} = \left\{ \sqrt{2}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \sqrt{2}\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}, \sqrt{2}\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \right\}$$

$$k_p = \frac{1}{\sqrt{2}} \begin{bmatrix} S_{hh} + S_{vv} \\ S_{hh} - S_{vv} \\ 2\,S_{hv} \end{bmatrix}$$

$$T = \langle k_p k_p^t \rangle = \frac{1}{2} \begin{bmatrix} \langle (S_{hh}+S_{vv})(S_{hh}+S_{vv})^{¿} \rangle & \langle (S_{hh}+S_{vv})(S_{hh}-S_{vv})^{¿} \rangle & 2\langle (S_{hh}+S_{vv}) S_{hv}^{¿} \rangle \\ \langle (S_{hh}-S_{vv})(S_{hh}+S_{vv})^{¿} \rangle & \langle (S_{hh}-S_{vv})(S_{hh}-S_{vv})^{¿} \rangle & \langle (S_{hh}-S_{vv}) S_{hv}^{¿} \rangle \\ 2\langle S_{hv} (S_{hh}+S_{vv})^{¿} \rangle & 2\langle S_{hv} (S_{hh}-S_{vv})^{¿} \rangle & 4\langle S_{hv} S_{hv}^{¿} \rangle \end{bmatrix}$$

from which the real diagonal terms represent the backscattering power, and the off diagonal terms the correlation between polarizations, from which scattering symmetries can be derived:

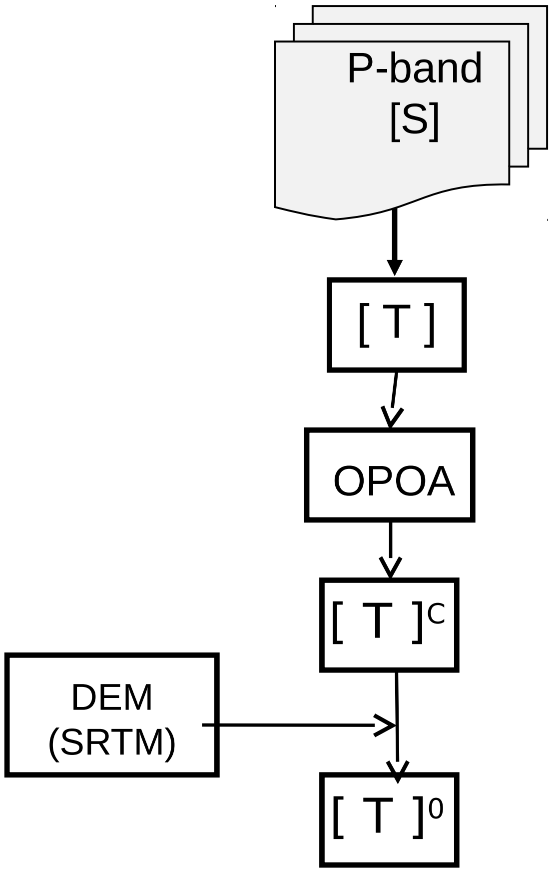
Composite RGB image resulting from the Pauli decomposition (<HH-VV>,<HV>,<HH+VV>)



Polarisation Orientation Angle (POA) derived from symmetric properties of the [T] matrix

Images from the TropiSAR airborne campaign in French Guiana

PolSAR based indicator : the t^0 coefficient



Scattering matrix

Coherency matrix

Optimal Polarisation Orientation Angle

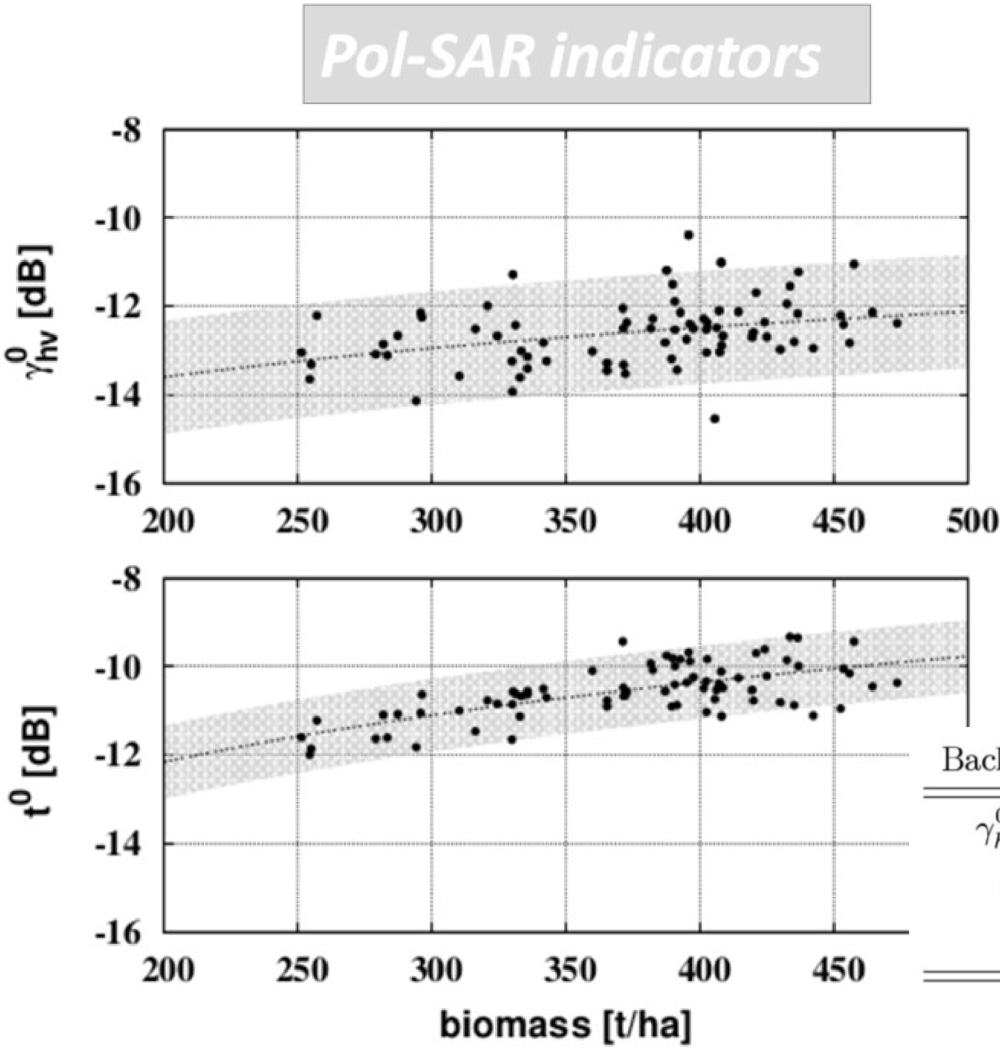
Non-linear optimisation technique to minimize

$$\mathcal{F} = |t_{13}^{\Theta}|^2 + |t_{23}^{\Theta}|^2$$

$$\left\{ \begin{array}{l} t_{11}^{\theta} = t_{11} \\ t_{13}^{\theta} = -t_{12} \cdot \sin 2\theta + t_{13} \cdot \cos 2\theta \\ t_{23}^{\theta} = -t_{23}^{*} \cdot \sin^2 2\theta + t_{23} \cdot \cos^2 2\theta + \frac{1}{2}(t_{33} - t_{22}) \cdot \sin 4\theta \\ t_{33}^{\theta} = \frac{1}{2}(t_{33} + t_{22}) + \frac{1}{2}(t_{33} - t_{22}) \cos 4\theta - \Re\mathrm{e}(t_{23}) \sin 4\theta \\ t_{22}^{\theta} = SPAN - t_{11}^{\theta} - t_{33}^{\theta}. \end{array} \right\}$$

*L. Villard et al. 'Biomass indicator for Tropical Dense Forests over Hully terrains from P-band SAR intensity : γ^0 or t^0 ?', Jan 2015, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (JSTARS).

PolSAR based indicator : the *t⁰* coefficient



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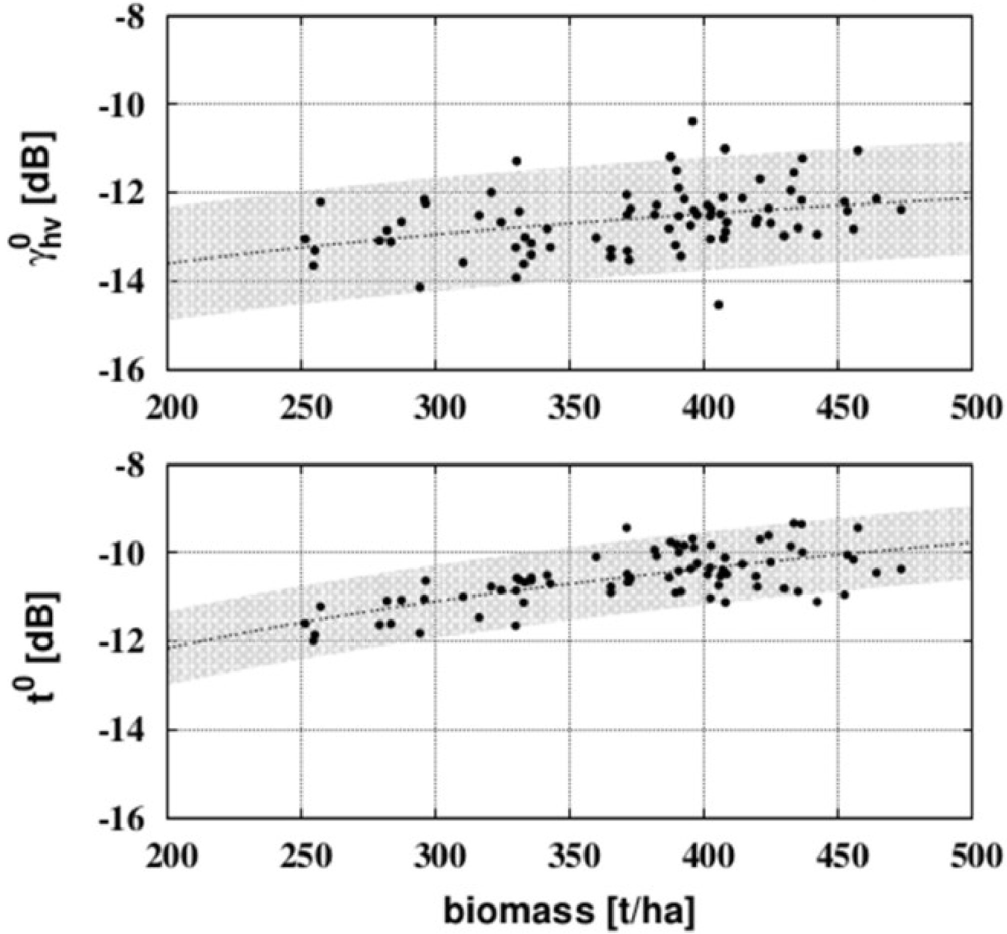
$$\gamma^0_{hv}[dB], t^0[dB], h[m] = a_1 \cdot \log_{10}(AGB[t/ha]) + a_0$$

PolSAR based indicator : the t^0 coefficient

Pol-SAR indicators



What we learn & develop from TropiSAR data

Topographic effects originate important dispersion regarding the backscatter sensitivity to AGB for high biomass values (> 200 t/ha),
→ standard backscattering coefficients are poorly correlated to AGB

To remove these perturbations and recover sensitivity to biomass, the ad-hoc PolSAR backscatter coefficient t^0 has been developed

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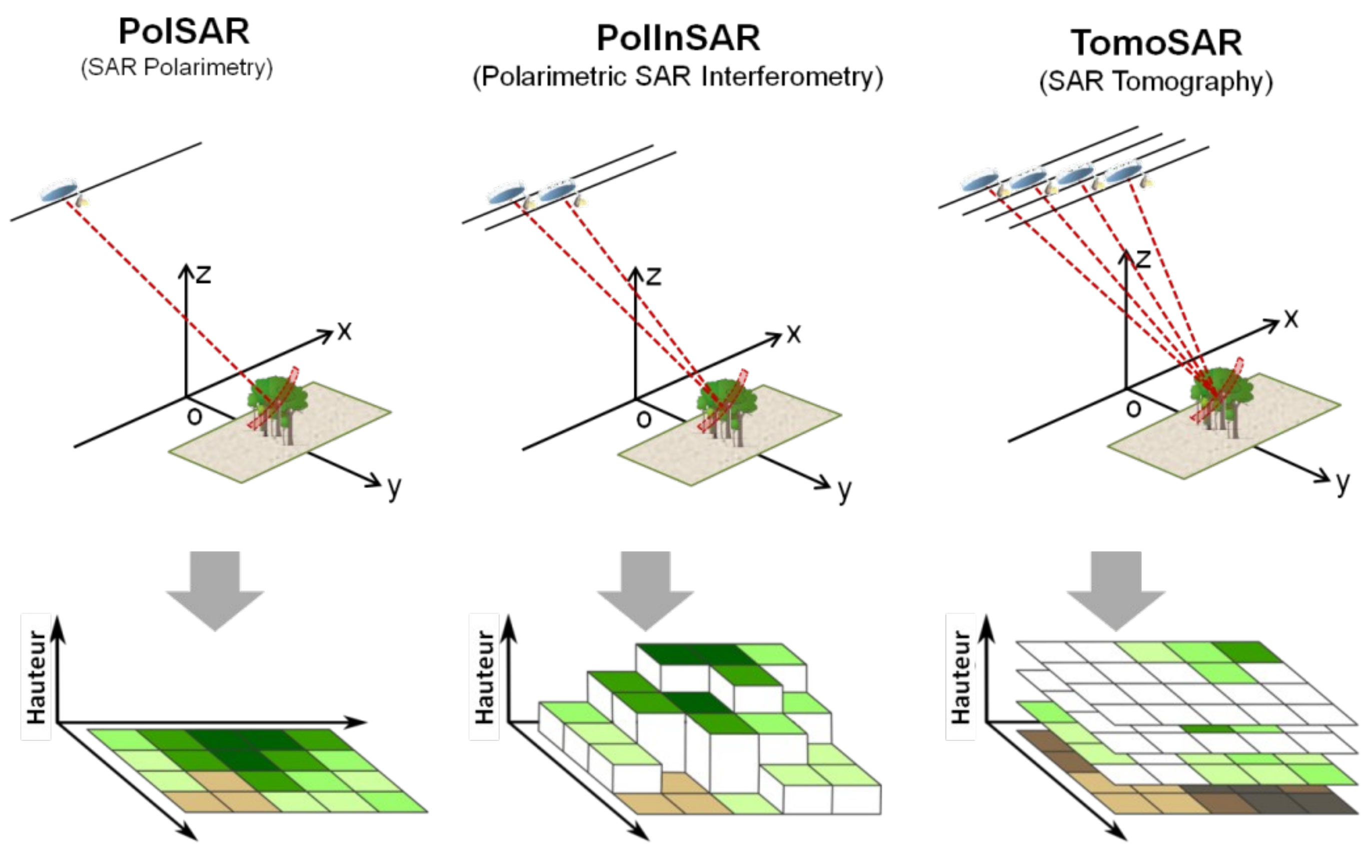
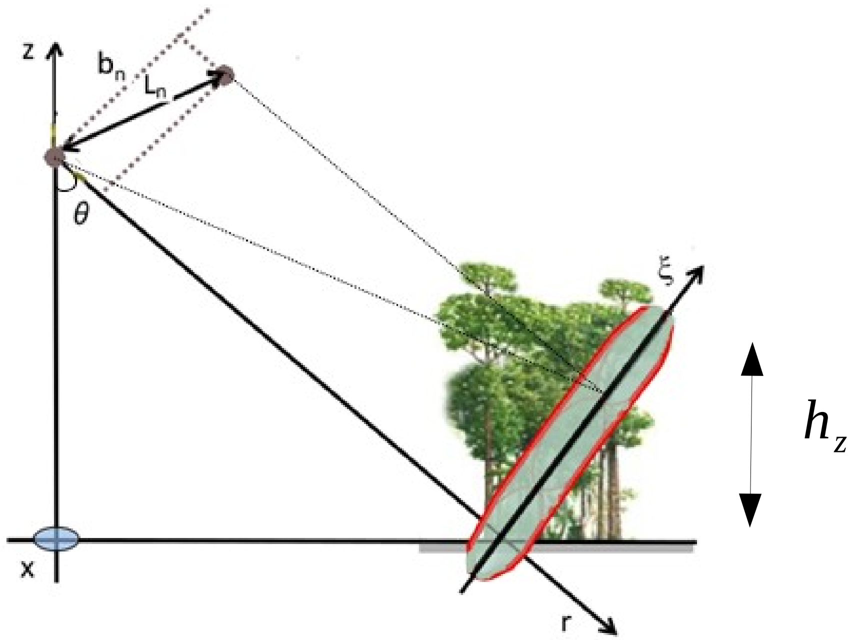
Acquisitions modes



These capabilities enable to increase the set of observations,
in order to enhance the underlying physical information

PolInSAR acquisitions



PolInSAR configuration defined by the baseline, and the type of acquisitions : **repeat-pass** or **bistatic**

$$h_a = \frac{\lambda . R . \sin(\theta_i)}{2 b_n}$$

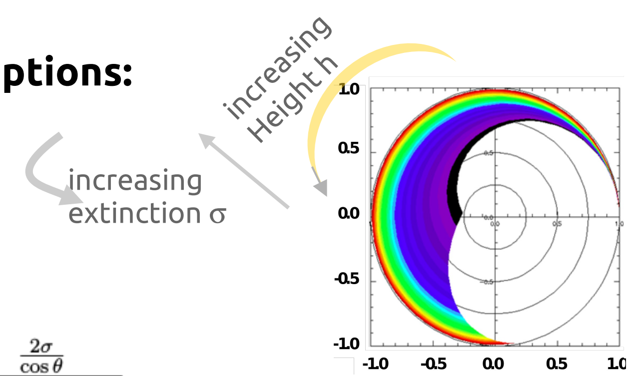
Phase center height given by:

$$h_z = \frac{\varphi_{12}}{2\pi} h_a$$

How to get vegetation height from the phase center height ?

'RvoG' model formulation, under the assumptions:

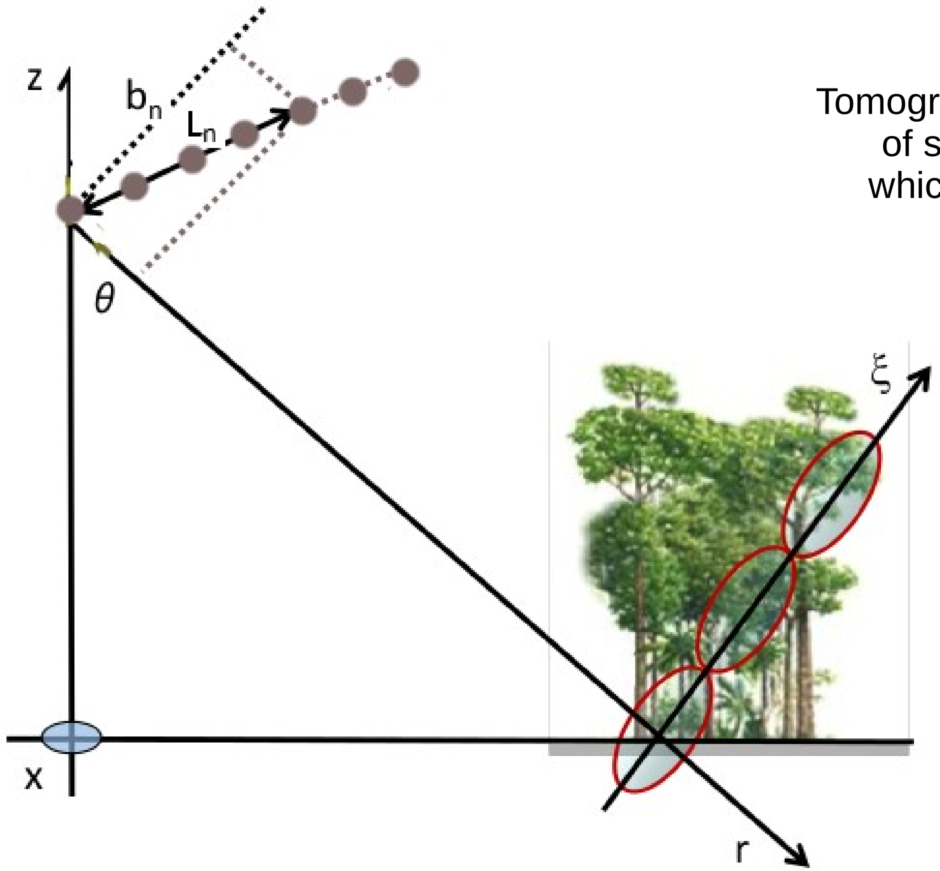
→ Random Volume Over Ground
→ zero ground contribution in HV



$$\gamma_{qp}^{vlm} = e^{j\Phi_0^{(v)}} \frac{\int_0^h e^{j\alpha_z z} \exp[\varpi_{qp}^{v} \cdot z] dz}{\int_0^h \exp[\varpi_{qp}^{v} \cdot z] dz}$$

$$\gamma_v = f_\sigma(h) = e^{j\Phi_0} \frac{I}{I_0} = e^{j\Phi_0} \frac{\exp(\frac{2\sigma h_v}{\cos\theta} + j\alpha_z h) - 1}{\frac{2\sigma}{\cos\theta} + j\alpha_z} \frac{\frac{2\sigma}{\cos\theta}}{\exp(\frac{2\sigma h}{\cos\theta}) - 1}$$

TomoSAR acquisitions



Tomographic SAR is based on the combination of several acquistions from different tracks, which enable to isolate voxels within an iso-range volume

Vertical resolution is given by :

$$\delta z = \frac{\lambda . R . \sin(\theta_i)}{2 b_n^{max}}$$

assuming a sufficient sampling (cf. Nyquist criteria) from several tracks closer than :

$$b_n^{min} = \frac{\lambda . R . \sin(\theta_i)}{2H}$$

Observation from acquisition 'n' :

$$y_n(r, x) = \int S(\xi, r, x) e^{j k_z^n \xi} d\xi$$

Estimated backscatter for each voxel:

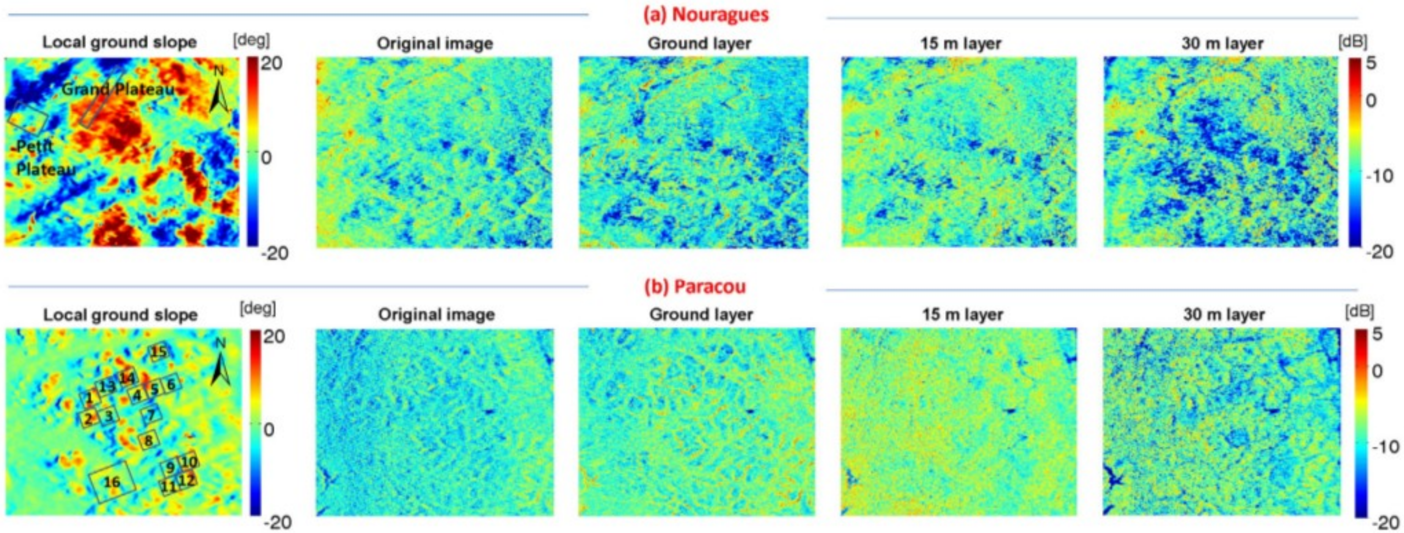
$$\boxed{\hat{S}(\xi, r, x) = \sum_{1 \le n \le N} y_n(r, x) e^{-j k_z^n \xi}}$$

TomoSAR based results from TropiSAR data

Paracou

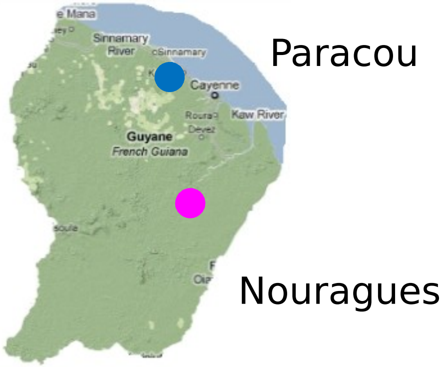
Nouragues

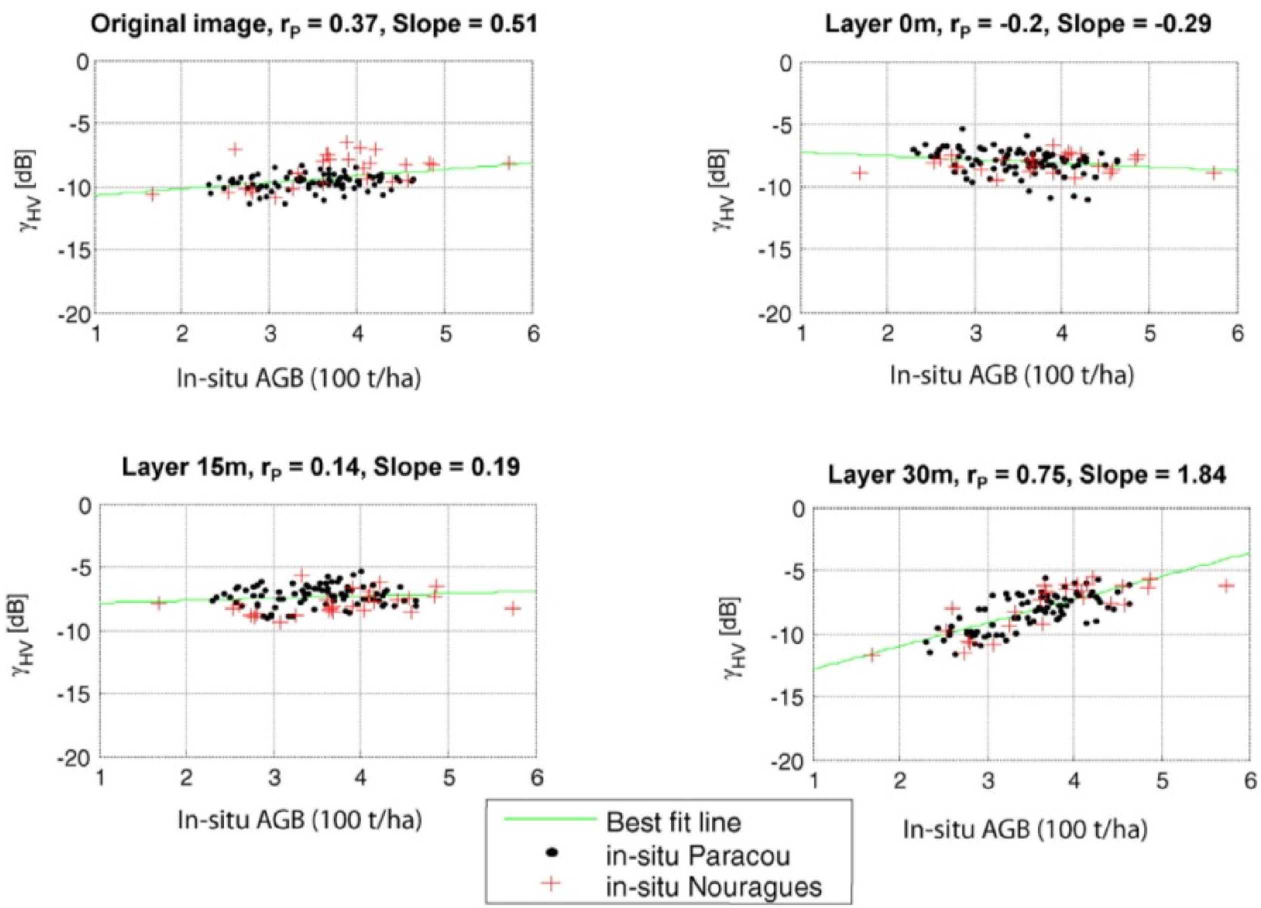
TomoSAR 3D layers from TropiSAR data in French Guiana for the 2 main test sites



D. Ho Tong Minh et al., Remote Sensing of Environment 175 (2016) 138–147

TomoSAR based results from TropiSAR data





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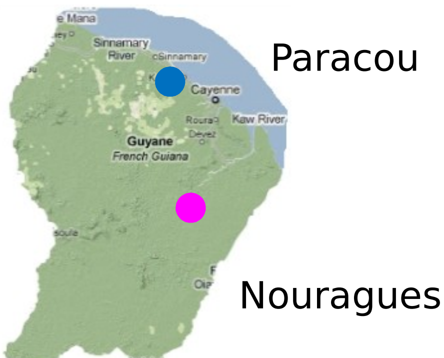
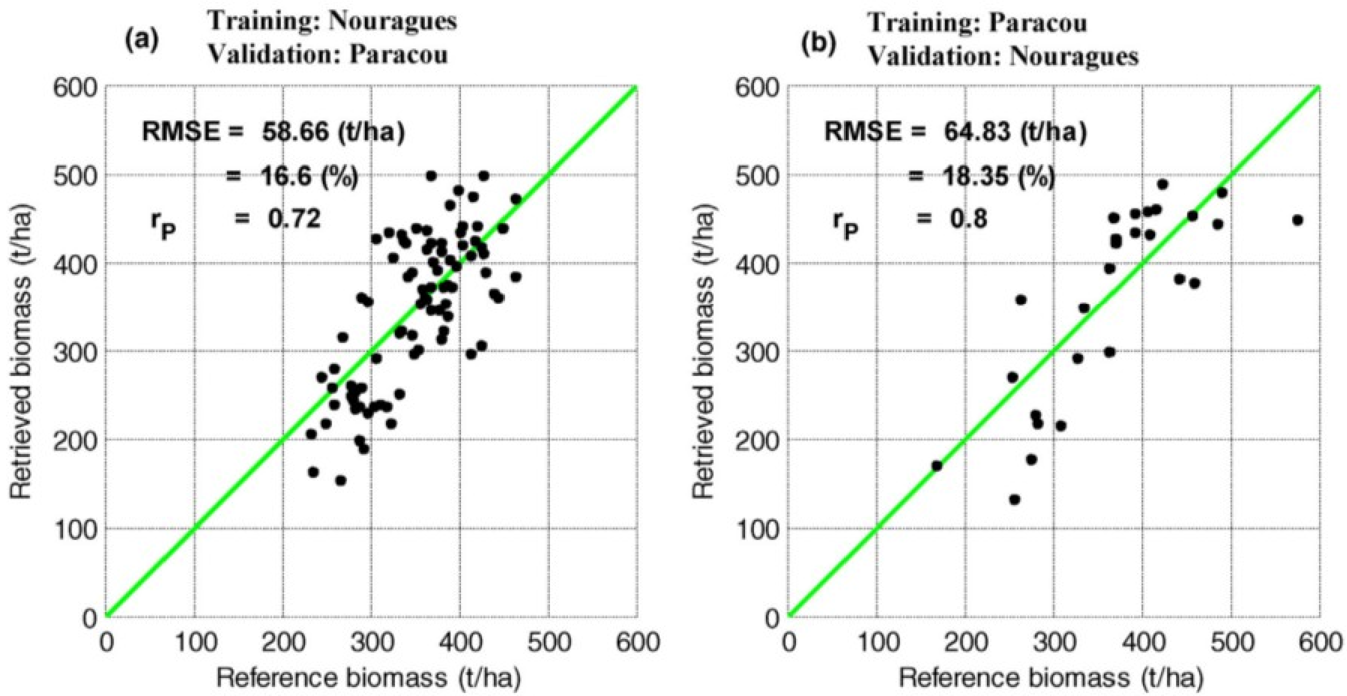
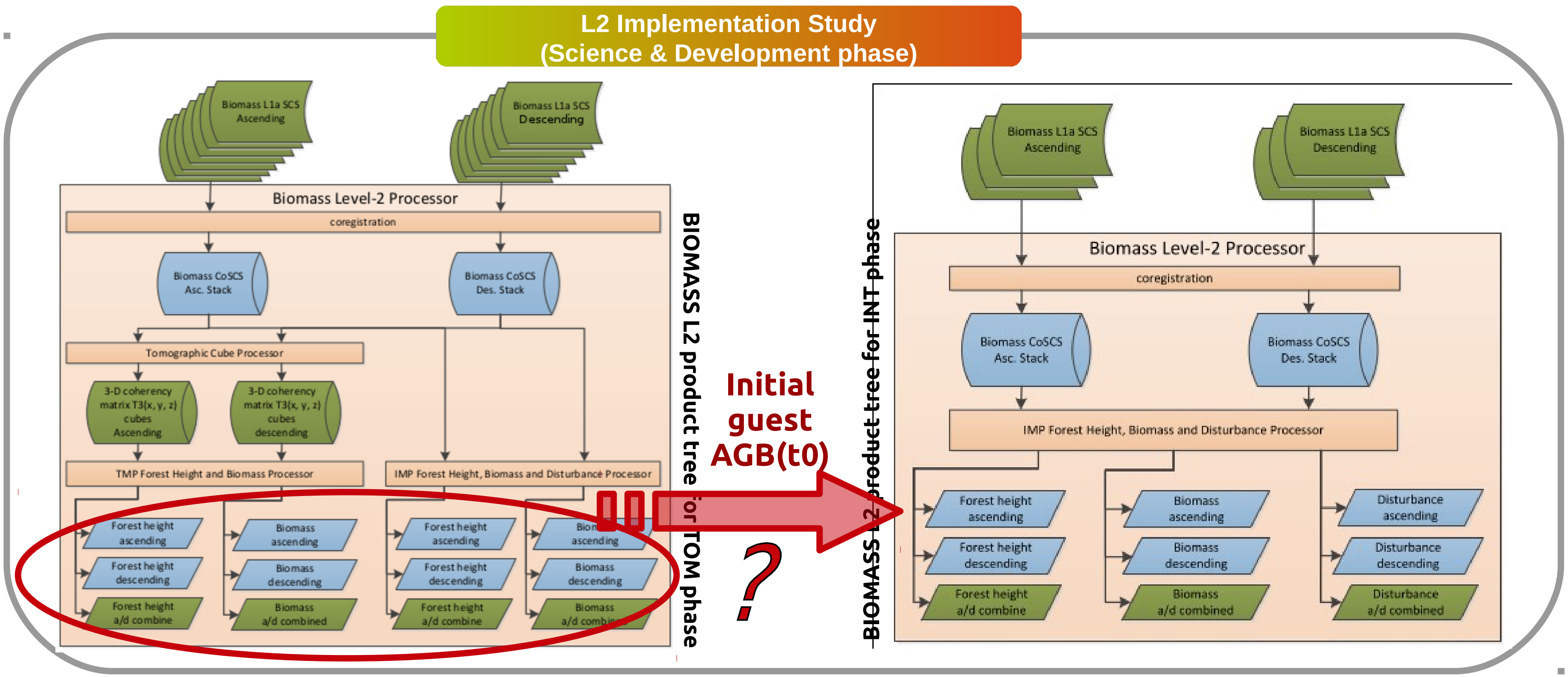




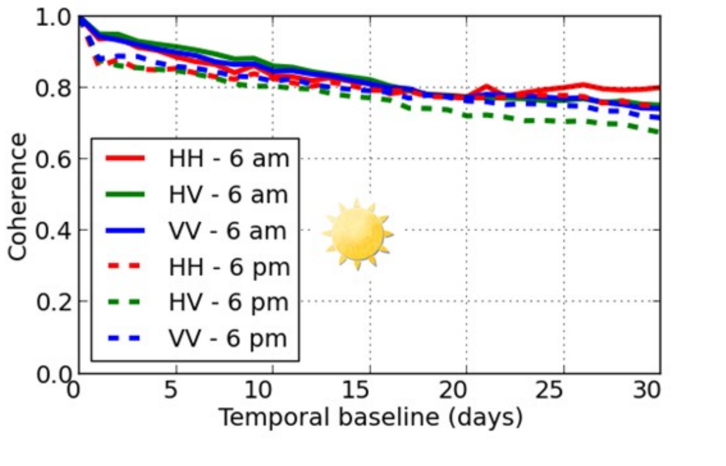
D. Ho Tong Minh et al., Remote Sensing of Environment 175 (2016) 138–147

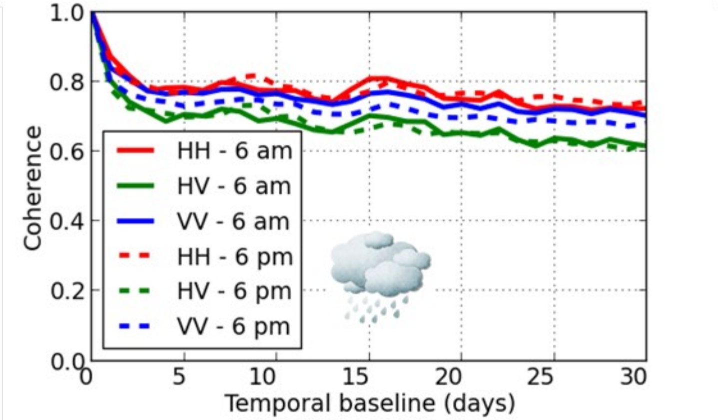
Given these (airborne) results, why not using AGB directly as initial guest and focus on changes with PolSAR/PolInSAR ?



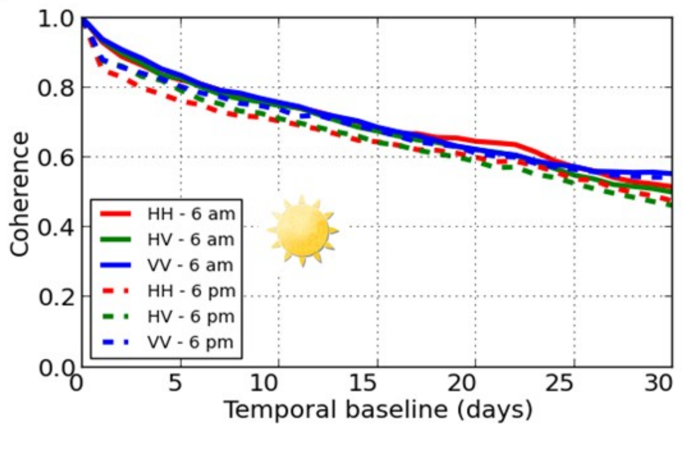
Temporal decorrelation analysis from tower based scatterometers

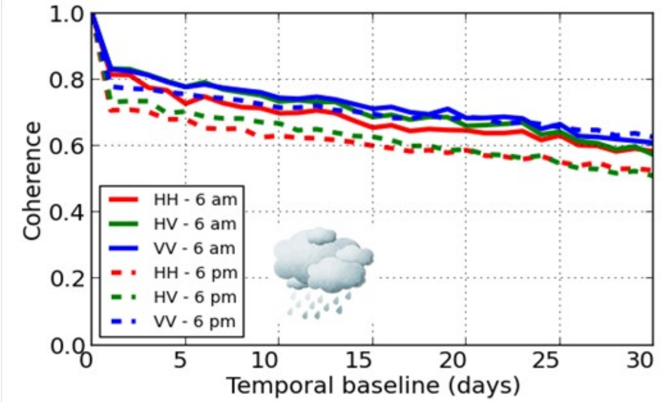
TropiScat





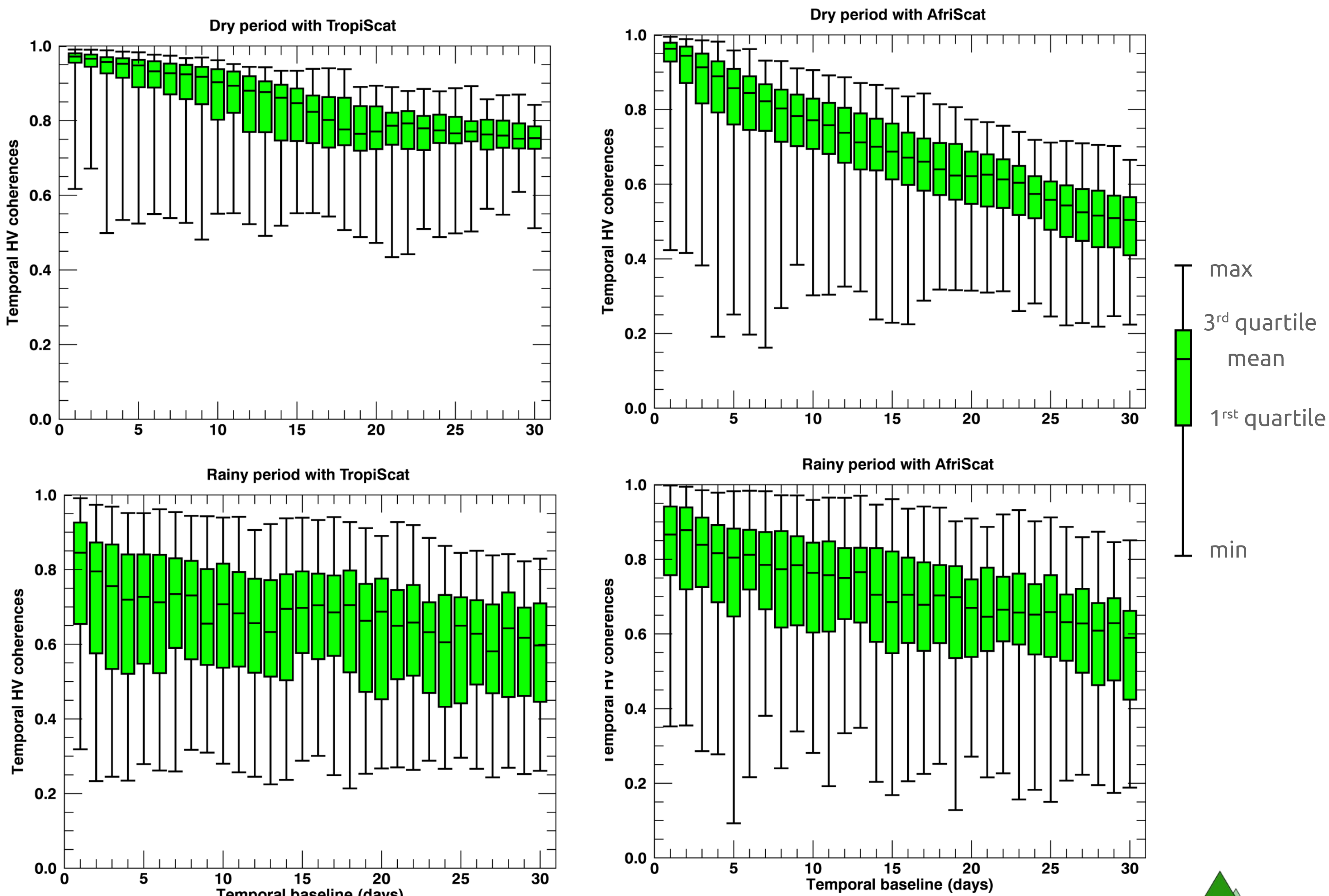
AfriScat





Temporal decorrelation analysis from tower based scatterometers

HV Tropiscat –Afriscat temporal coherences, 6 am, dry period (top) vs rainy period (bottom)



TropiScat **AfriScat**

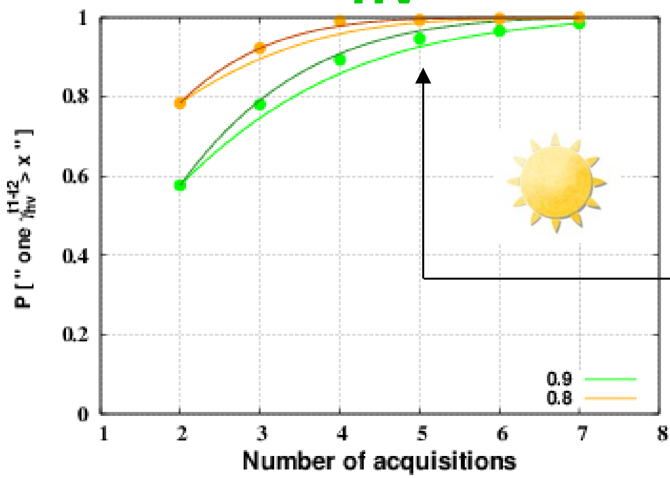
Biomass mission scenario: Probabilities to get at least one pair (optimal for PolInSAR) with $\gamma(t,t+3)$ > [0.8,0.9] with N acquisitions

(from AfriScat statistical results at 6 am±30min, for dry & rainy periods)

Event “E08”: “at least one $\gamma(t,t+3) \geq 0.8$”
Event “E08”: “all pairs \ $\gamma(t,t+3) < 0.8$”

P(E08) = 1-P(E08)

HV

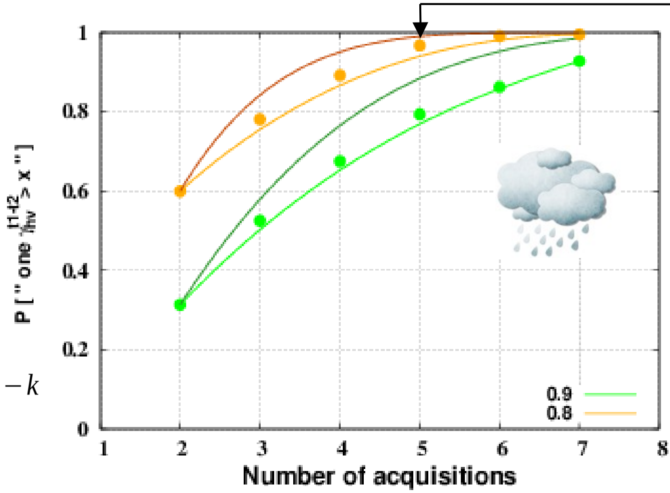


Points & bottom lines :
To account for the dependency between pairs, all set of uplets from N acquisitions have been generated, from which only the optimal pairs (t,t+3) have been considered (from 2 to 6 pairs for 2≤N≤7)

Examples :

5 acquisitions enable to reach the 95% confidence interval to get at least one (t,t+3) pair with coherence greater than 0.9

5 acquisitions enable to reach the 95% confidence interval to get at least one (t,t+3) pair with coherence greater than 0.8



Upper bound (top darker lines):
Case of independence between all possible pairs with N acqs,
from 2 to 21 pairs for 2≤N≤7)

$$P\left(\overline{E\,08}\right) = \prod_{k=1}^{N-1} \left(1 - p\left\{\gamma\left(t, t+3k\right) \geq 0.8\right\}\right)^{N-k}$$

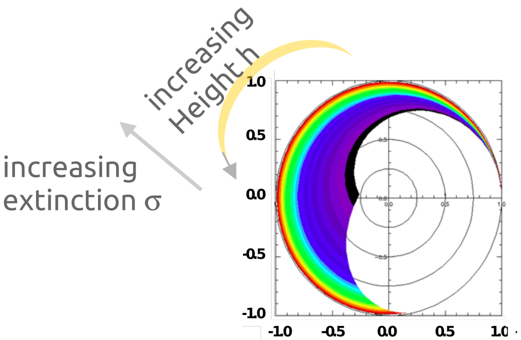
Impact of temporal decorrelation on PolInSAR height retrieval

Main assumptions:

→ Random Volume Over Ground
→ zero ground contribution in HV

$$\gamma_{qp}^{vlm} = e^{j\Phi_0^{(v)}} \frac{\int_0^h e^{j\alpha_z z} \exp[\varpi_{qp}^v \cdot z]dz}{\int_0^h \exp[\varpi_{qp}^v \cdot z]dz}$$

$$\gamma_v = f_\sigma(h) = e^{j\Phi_0}\frac{I}{I_0} = e^{j\Phi_0}\frac{\exp(\frac{2\sigma h_v}{\cos\theta} + j\alpha_z h) - 1}{\frac{2\sigma}{\cos\theta} + j\alpha_z}\frac{\frac{2\sigma}{\cos\theta}}{\exp(\frac{2\sigma h}{\cos\theta}) - 1}$$



Retrieval performances on height and extinction:

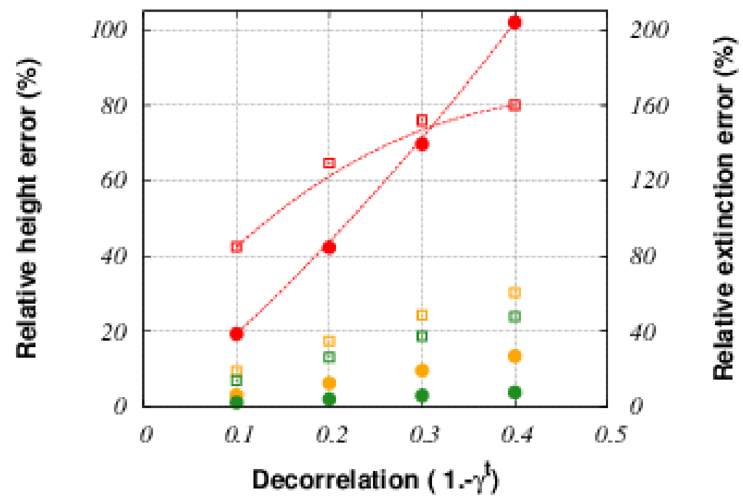
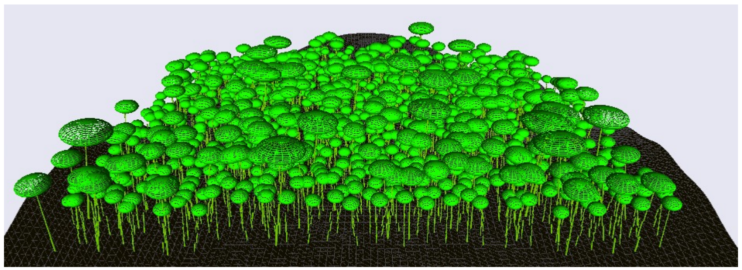
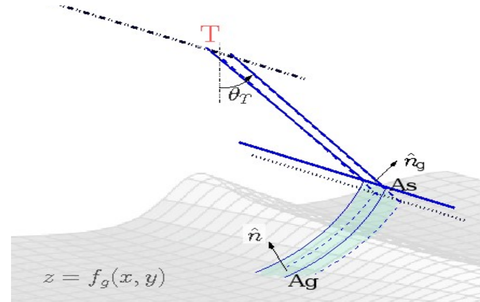


Fig : Theoretical relative percentage error as a function of deccorrelation magnitude, for both estimated forest height and extinction coefficient based on the RVoG model, and using a multiplicative real factor gamma_t to simulate decorrelation. The reference extinction coefficient has been set to 0.06 Np (typical value at P-band) ambiguity height to 30m, whereas the targeted forest heights (10, 20 and 30m) are respectively represented in red, orange and dark green

Alternative approach :
use of forward EM model [MIPERS4D] to build build likelihood functions
(and generate lookup table i.o analytical formulation)

Scene & observation geometry

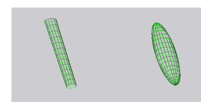




$$\frac{d\langle E_v\rangle}{dr} = j(k_0 - \frac{\sigma_{vv}}{2})\langle E_v\rangle - j\frac{\sigma_{vh}}{2}\langle E_h\rangle$$

$$\frac{d\langle E_h\rangle}{dr} = -j\frac{\sigma_{hv}}{2}\langle E_v\rangle + j(k_0 - \frac{\sigma_{hh}}{2})\langle E_h\rangle$$

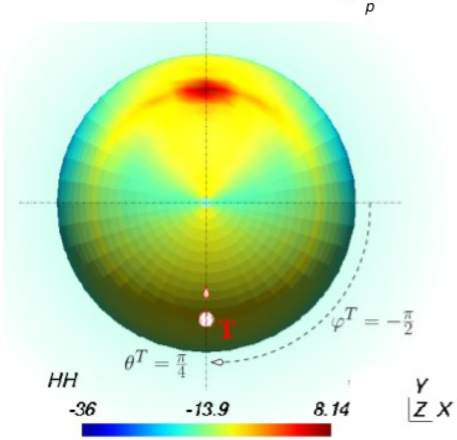
with : $\sigma_{qp}(\theta, \phi) = \frac{4\pi n_0}{k_0}\langle Im(S_{qp}(\theta, \phi))\rangle_{p,o,s}$



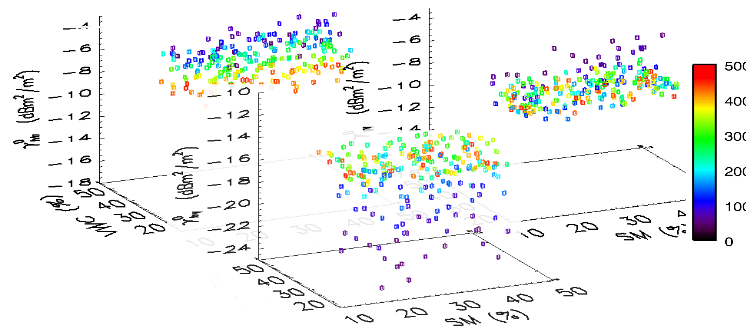
canonical shapes

Coherent modeling
based on the DBWA
(Distorted Born Wave
Approximation)

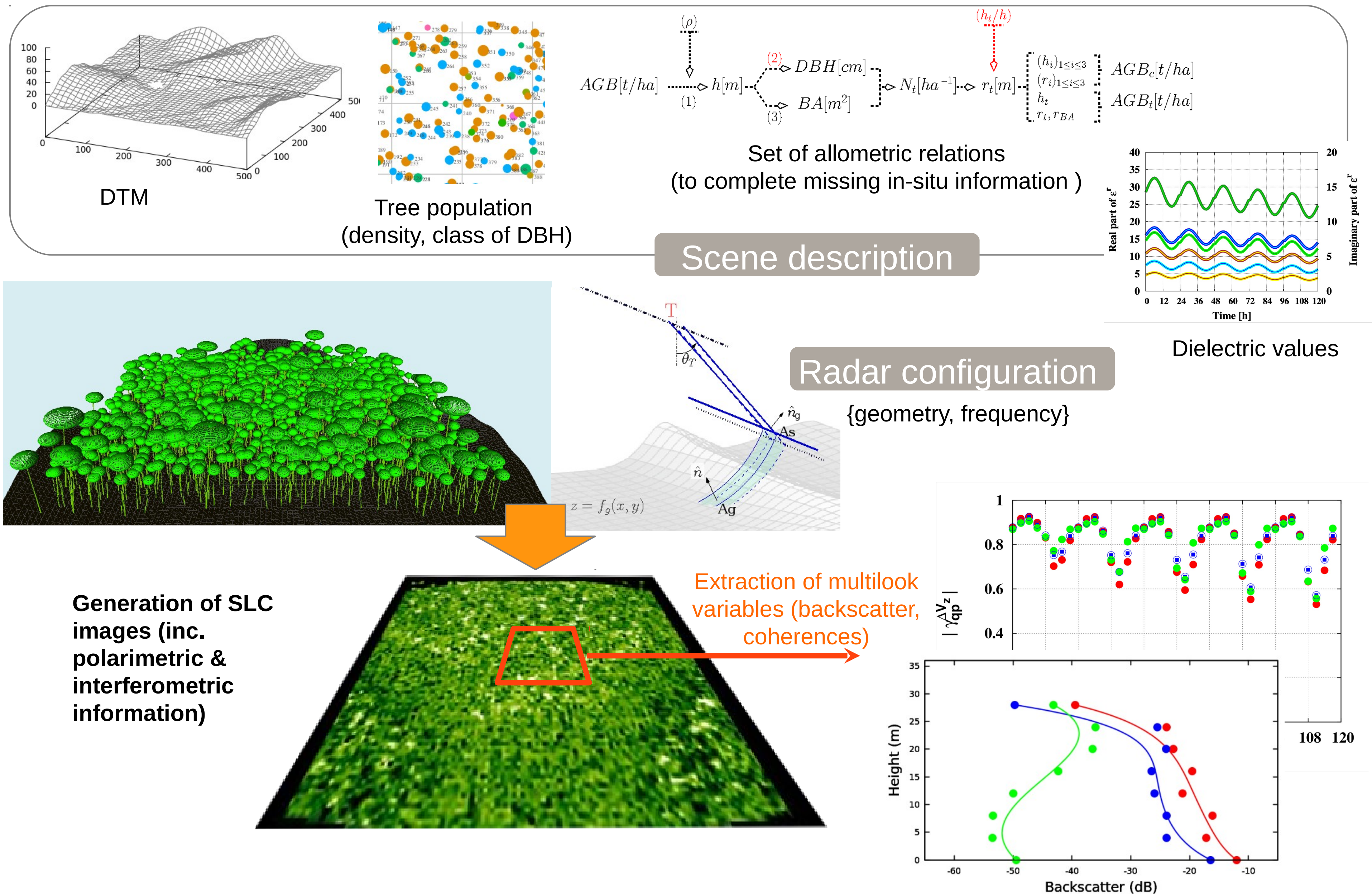
$$\mathbf{E}_s(\vec{r}_R; \vec{r}_T) = \left(\sum_p e^{-j\varphi_p^{ds}}[t_p(\hat{k}_s)] \cdot [S_p(\hat{k}_i, \hat{k}_s)] [t_p(\hat{k}_i)]\right) \cdot \mathbf{E}_i(\hat{k}_i)$$



Simulated SAR measurements

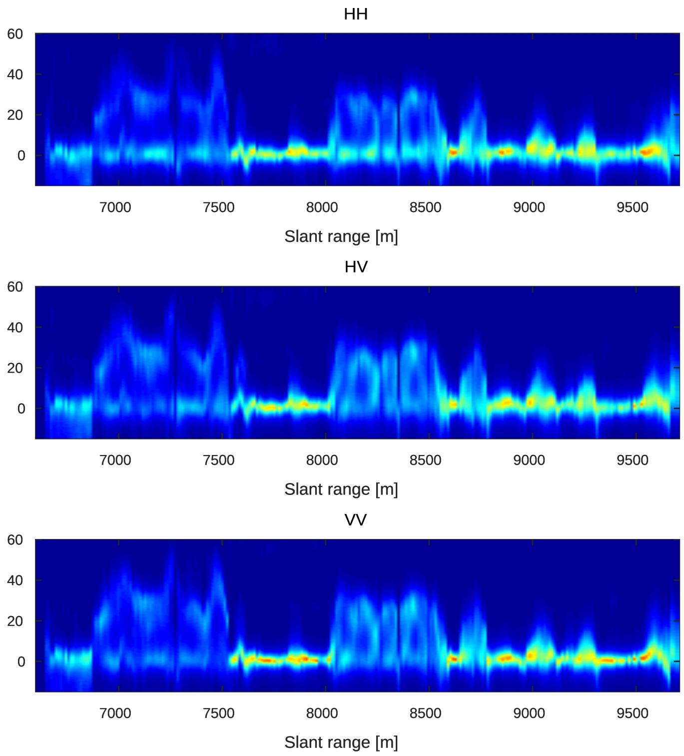


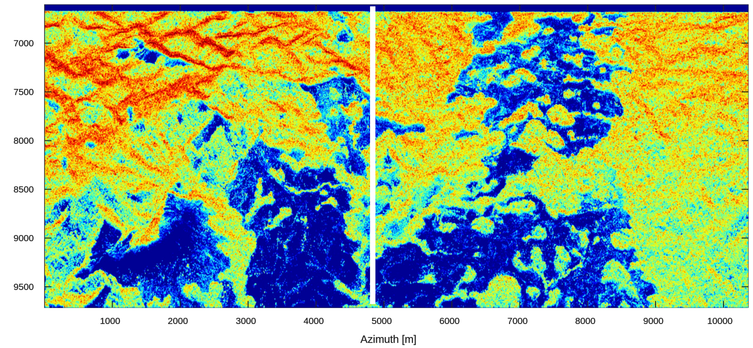
Use of MIPERS^{4D} : inputs & outputs



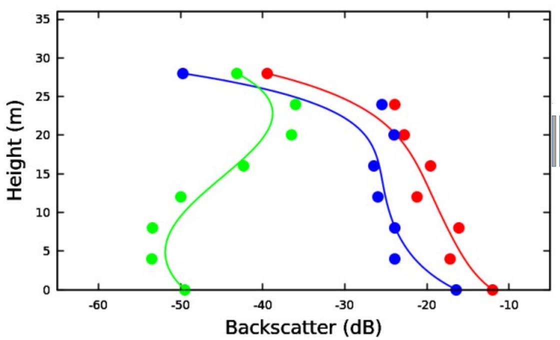
Alternative approach : use of forward EM model to build build likelihood functions
(and generate lookup table i.o analytical formulation)

Vertical backscatter disttribution
along the transect





Backscatter image at Lopé test site (with white transect



For this study:
Parameterization
limited to total height
and top layer
(given larger
uncertainties for the
HV bottom layer)

Alternative approach : use of forward EM model to build build likelihood functions
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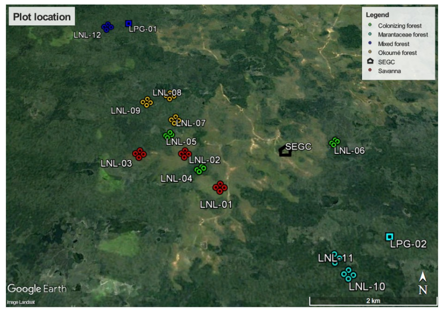
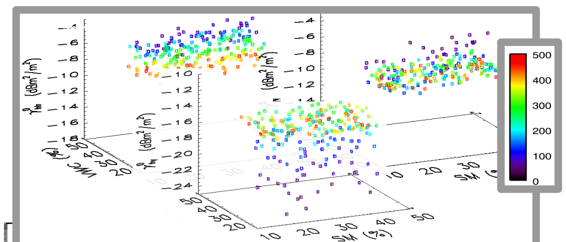
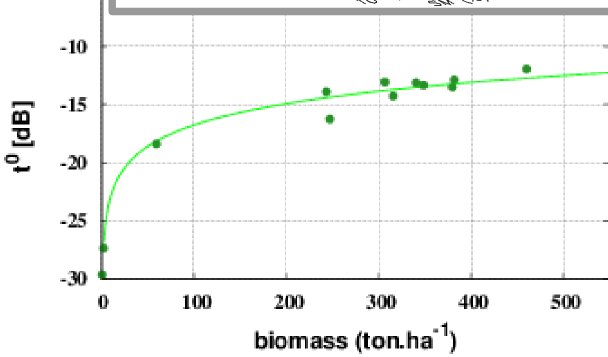
Set of in-situ plots

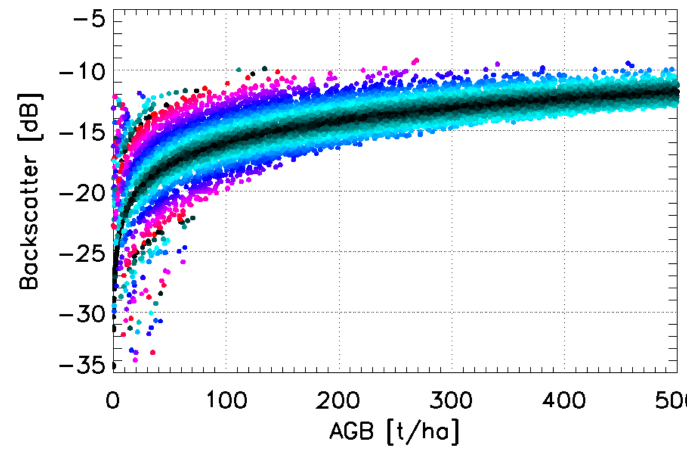


Simulated database
(transferability)



Calibrated
indicator





Parametrized power law from the
MIPERS^{4D} look-up table

Alternative approach : use of forward EM model to build build likelihood functions
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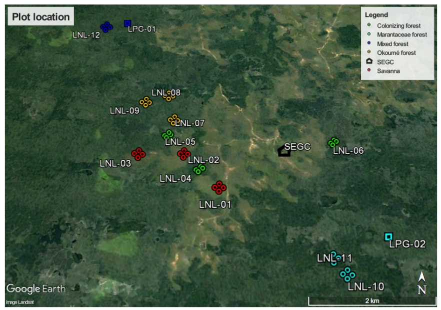
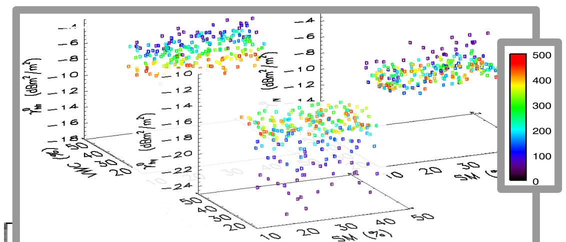
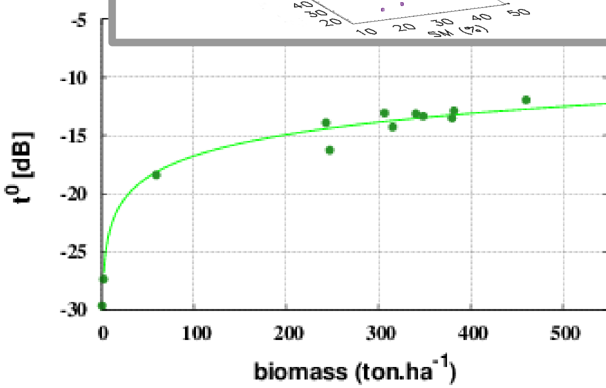
Set of in-situ plots

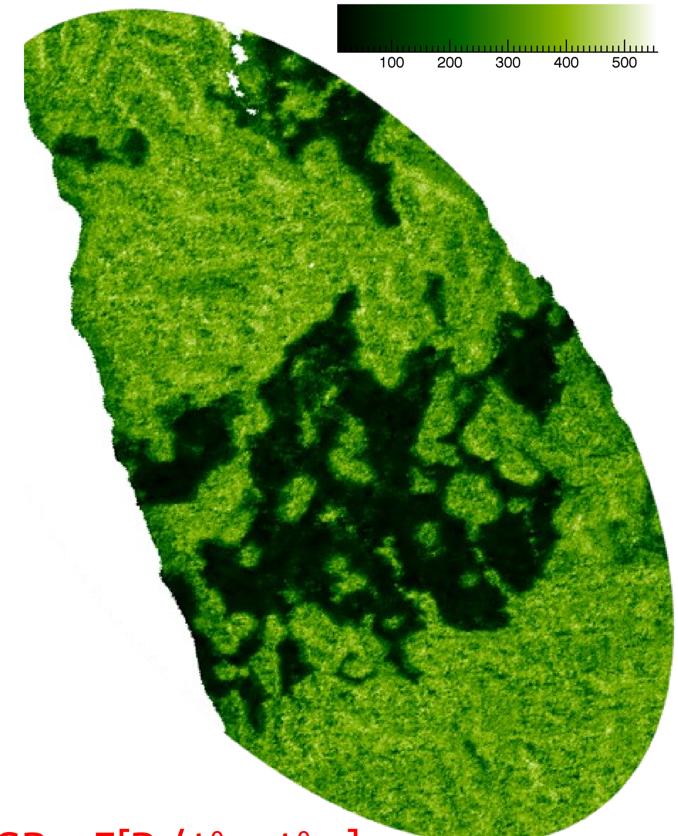


Simulated database
(transferability)



Calibrated
indicator





$$AGB = E[B \,/\, t^0_{asc}, t^0_{dsc}]$$
$$= \int B \cdot p_{asc}(t^0_{asc} \,/\, B) \cdot p_{dsc}(t^0_{dsc} \,/\, B)\, dB$$

MMSE based on the conditional expectancy
buildt in the likelihood functions

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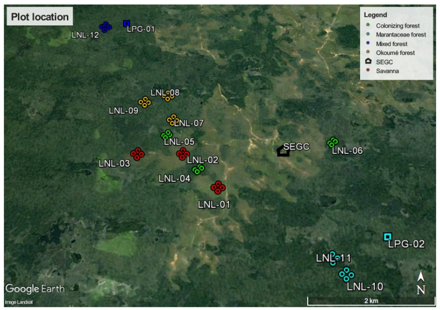

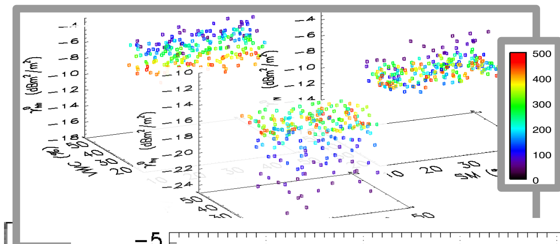

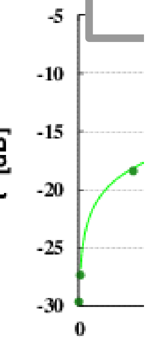

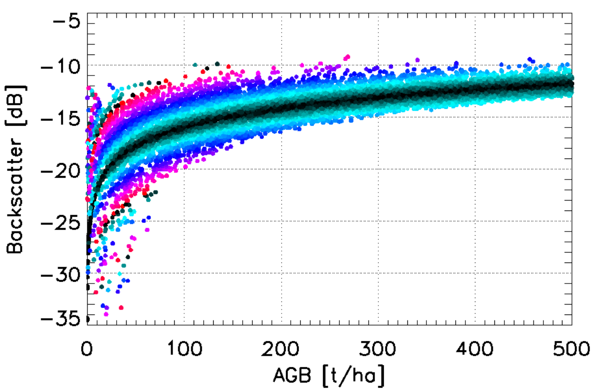

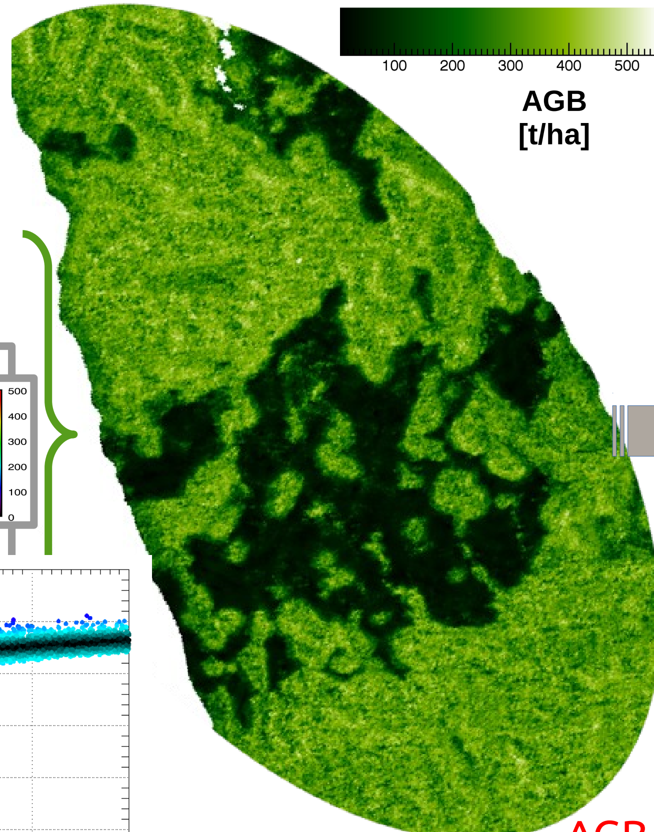

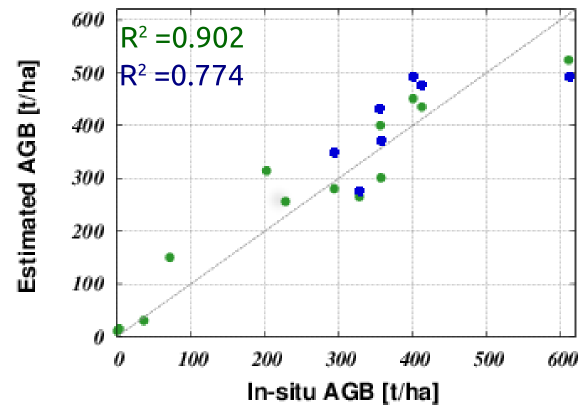

$$AGB = E[B \,/\, t^0_{asc}, t^0_{dsc}]$$
$$= \int B \cdot p_{asc}(t^0_{asc} / B) \cdot p_{dsc}(t^0_{dsc} / B)\, dB$$

MMSE based on the conditional expectancy
buildt in the likelihood functions

Synthesis & perspectives

- Importance of experimental campaigns :

  from the initial development to the performance analysis in spaceborne mission scenario

- Importance of EM modeling and the devolpement of EM models
for data analysis and a better used of exp data in retrieval algorithms

- But beyond theses studies….not doubt that we will learn a lot with BIOMASS P-band data,
over forested lands but also on many over landscapes and fields of research !

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