Underlying Topography Estimation and Separation of Scattering Contributions over Forests Based on PolInSAR Data

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Fringe-2011

September-2011
Fracatti, Italy

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Outline

- RVoG coherent scattering model
- Separation of scattering contributions
- Retrieval of interferometric information
- Validation based on Simulated PolInSAR data
- Validation based on Real PolInSAR data

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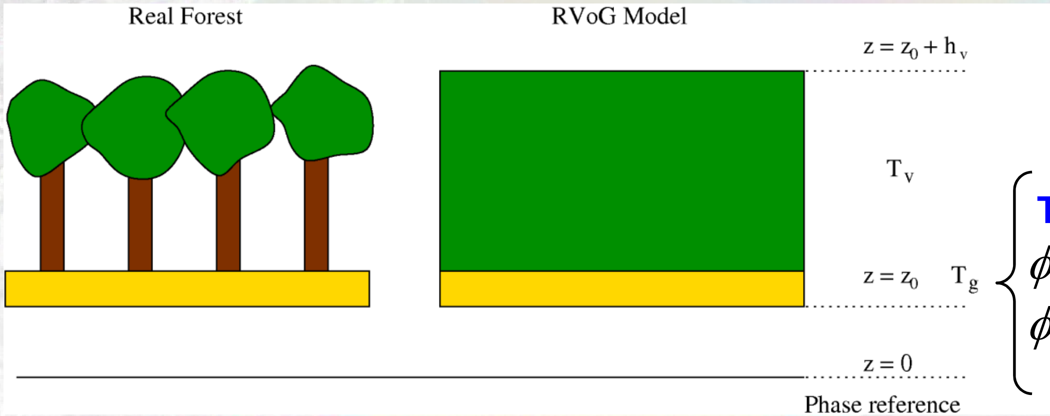
Polarimetric SAR Interferometry

Random Volume over Ground RVoG coherent scattering model



Topo. phase

ϕ_1 : topo. phase

ϕ_2 : canopy bottom phase

$$\mathbf{T}_6 = \begin{bmatrix} \mathbf{T}_{11} & \mathbf{\Omega}_{12} \\ \mathbf{\Omega}_{21} & \mathbf{T}_{22} \end{bmatrix}$$

PolInSAR coherency matrix

- PolSAR information

$$\mathbf{T}_{11} = \mathbf{T}_{22} = \mathbf{I}_1^v + e^{-\frac{2\sigma h_v}{\cos\theta_0}} \mathbf{I}_1^g$$

$$\mathbf{I}_1^v = e^{-\frac{2\sigma h_v}{\cos\theta_0}} \int_0^{h_v} e^{\frac{2\sigma z'}{\cos\theta_0}} \mathbf{T}_v dz' \qquad \mathbf{I}_1^g = \int_0^{h_v} \delta(z') e^{\frac{2\sigma z'}{\cos\theta_0}} \mathbf{T}_g dz' = \mathbf{T}_g$$

- PolInSAR information

$$\mathbf{\Omega}_{12} = e^{j\phi_2} \mathbf{I}_2^v + e^{j\phi_1} e^{-\frac{2\sigma h_v}{\cos\theta_0}} \mathbf{I}_2^g$$

$$\mathbf{I}_2^v = e^{-\frac{2\sigma h_v}{\cos\theta_0}} \int_0^{h_v} e^{j\kappa_z z'} e^{\frac{2\sigma z'}{\cos\theta_0}} \mathbf{T}_v dz' \qquad \mathbf{I}_2^g = \int_0^{h_v} \delta(z') e^{\frac{2\sigma z'}{\cos\theta_0}} \mathbf{T}_g dz' = \mathbf{T}_g$$

Volume contribution

$$\mathbf{T}_v = m_v \begin{bmatrix} 1 & 0 & 0 \\ 0 & \eta & 0 \\ 0 & 0 & \eta \end{bmatrix}$$

Ground contribution

$$\mathbf{T}_g = m_g \begin{bmatrix} 1 & t_{12} & 0 \\ t_{12}^* & t_{22} & 0 \\ 0 & 0 & t_{33} \end{bmatrix}$$

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Polarimetric SAR Interferometry

Interferometric coherence under the hypothesis of the RVoG model

$$\rho(\mathbf{w}) = \frac{\mathbf{w}^H \mathbf{\Omega}_{12}\mathbf{w}}{\mathbf{w}^H \mathbf{T}_{11}\mathbf{w}} = e^{j\phi_1}\frac{\rho_v + m(\mathbf{w})}{1+m(\mathbf{w})}$$

$$m(\mathbf{w}) = \frac{m_g(\mathbf{w})}{m_v(\mathbf{w})I_0}$$

Ground-to-volume ratio

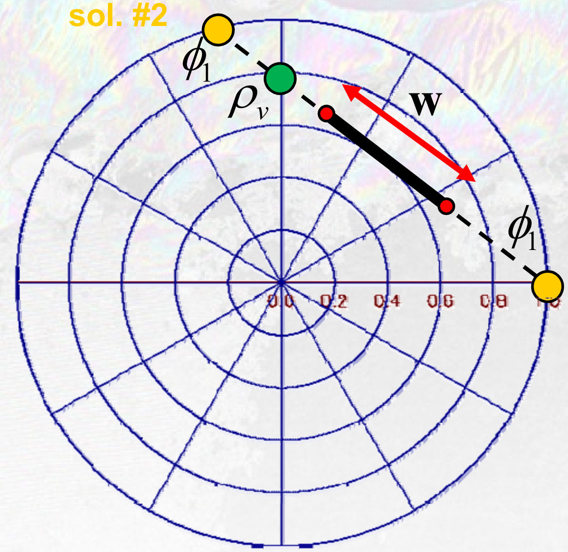
$$I = \int_0^{h_V} e^{j\kappa_z z'} \exp\left(\frac{2\sigma z'}{\cos\theta_0}\right)dz'$$

$$\rho_v = \frac{I}{I_0}$$

$$I_0 = \int_0^{h_V} \exp\left(\frac{2\sigma z'}{\cos\theta_0}\right)dz'$$

Volume coherence

$$\kappa_z = \frac{\kappa\Delta\theta}{\sin(\theta_0)}$$



No direct access neither to the underneath topography nor the volume coherence due to the limitation on the visible line length of the linear dependency of the interferometric coherence w.r.t. the polarization state

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PolInSAR Complex Correlation Coefficient

In the most general case, the complex correlation coefficient is defined in terms of two generalized scattering mechanisms

$$\rho(\mathbf{w}_1,\mathbf{w}_2)=\frac{\mathbf{w}_1^H\mathbf{\Omega}_{12}\mathbf{w}_2}{\sqrt{\mathbf{w}_1^H\mathbf{T}_{11}\mathbf{w}_1\mathbf{w}_2^H\mathbf{T}_{22}\mathbf{w}_2}}$$

Assumption of the RVoG model

$$\rho(\mathbf{w}_1,\mathbf{w}_2)=\frac{\mathbf{w}_1^H\mathbf{\Omega}_{12}\mathbf{w}_2}{\sqrt{\mathbf{w}_1^H\mathbf{T}_{11}\mathbf{w}_1\mathbf{w}_2^H\mathbf{T}_{11}\mathbf{w}_2}}$$

$$\rho(\mathbf{w}_1,\mathbf{w}_2)=\frac{\mathbf{w}_1^H\left(e^{j\phi_2}\mathbf{I}_2^v+e^{j\phi_1}e^{-\frac{2\sigma h_v}{\cos\theta_0}}\mathbf{I}_2^g\right)\mathbf{w}_2}{\sqrt{\mathbf{w}_1^H\left(\mathbf{I}_1^v+e^{-\frac{2\sigma h_v}{\cos\theta_0}}\mathbf{I}_1^g\right)\mathbf{w}_1\mathbf{w}_2^H\left(\mathbf{I}_1^v+e^{-\frac{2\sigma h_v}{\cos\theta_0}}\mathbf{I}_1^g\right)\mathbf{w}_2}}$$

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PolInSAR Complex Correlation Coefficient

Separation, in terms of the numerator, of the complex correlation coefficient, under the assumption of the RVoG coherent scattering model

$$\rho(\mathbf{w}_1,\mathbf{w}_2)=\rho_v(\mathbf{w}_1,\mathbf{w}_2)+\rho_g(\mathbf{w}_1,\mathbf{w}_2)$$

- Volume contribution

$$\rho_v(\mathbf{w}_1,\mathbf{w}_2)=\frac{e^{j\phi_2}\mathbf{w}_1^H\mathbf{I}_2^v\mathbf{w}_2}{\sqrt{\mathbf{w}_1^H\left(\mathbf{I}_1^v+e^{-\frac{2\sigma h_v}{\cos\theta_0}}\mathbf{I}_1^g\right)\mathbf{w}_1\mathbf{w}_2^H\left(\mathbf{I}_1^v+e^{-\frac{2\sigma h_v}{\cos\theta_0}}\mathbf{I}_1^g\right)\mathbf{w}_2}}$$

- Ground (double bounce) contribution

$$\rho_g(\mathbf{w}_1,\mathbf{w}_2)=\frac{e^{j\phi_1}e^{-\frac{2\sigma h_v}{\cos\theta_0}}\mathbf{w}_1^H\mathbf{I}_2^g\mathbf{w}_2}{\sqrt{\mathbf{w}_1^H\left(\mathbf{I}_1^v+e^{-\frac{2\sigma h_v}{\cos\theta_0}}\mathbf{I}_1^g\right)\mathbf{w}_1\mathbf{w}_2^H\left(\mathbf{I}_1^v+e^{-\frac{2\sigma h_v}{\cos\theta_0}}\mathbf{I}_1^g\right)\mathbf{w}_2}}$$

Cancelation, in terms of the numerator, of one of the previous components

- $\mathbf{w}_1,\mathbf{w}_2$ that cancel the volume or the ground contribution
- $\mathbf{w}_1,\mathbf{w}_2$ that cancel one component while maximizing the other one

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Cancelation of the Volume Component

Volume component can be cancelled considering

$$e^{j\phi_2}\mathbf{w}_1^H\mathbf{I}_2^v\mathbf{w}_2=0 \quad \Rightarrow \quad e^{j\phi_2}m_vC_v\mathbf{w}_1^H\begin{bmatrix}1&0&0\\0&\eta&0\\0&0&\eta\end{bmatrix}\mathbf{w}_2=0$$

$$C_v=e^{\frac{-2\sigma h_v}{\cos\theta_0}}\int_0^{h_v}e^{j\kappa_z z'}e^{\frac{2\sigma z'}{\cos\theta_0}}dz'$$

where: $\arg\{C_v\}=\arg\{\rho_v\}$

- Cancellation can be independent of the volume properties

$$\begin{bmatrix}w_{11}^* & w_{12}^* & w_{13}^*\end{bmatrix}\begin{bmatrix}1&0&0\\0&\eta&0\\0&0&\eta\end{bmatrix}\begin{bmatrix}w_{21}\\w_{22}\\w_{23}\end{bmatrix}=0$$

$$\begin{aligned}w_{11}^*w_{21}&=0\\w_{12}^*w_{22}+w_{13}^*w_{23}&=0\end{aligned}$$

- Optimization of the ground component can be considered

$$\begin{aligned}&\text{maximize} && |\rho(\mathbf{w}_1,\mathbf{w}_2)|\\&\text{subject to} && w_{11}^*w_{21}=0\\& && w_{12}^*w_{22}+w_{13}^*w_{23}=0\\& && \mathbf{w}_1^H\mathbf{T}_{11}\mathbf{w}_1=ct\\& && \mathbf{w}_2^H\mathbf{T}_{11}\mathbf{w}_2=ct\end{aligned}$$

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Cancelation of the Ground Component

Ground (double bounce) component can be cancelled considering

$$e^{j\phi_1} e^{-\frac{2\sigma h_v}{\cos\theta_0}} \mathbf{w}_1^H \mathbf{I}_2^g \mathbf{w}_2 = 0 \quad \Rightarrow \quad e^{j\phi_1} e^{-\frac{2\sigma h_v}{\cos\theta_0}} m_g \mathbf{w}_1^H \begin{bmatrix} 1 & t_{12} & 0 \\ t_{12}^* & t_{22} & 0 \\ 0 & 0 & t_{33} \end{bmatrix} \mathbf{w}_2 = 0$$

- Cancelation is performed using different normalized eigenvectors of the ground scattering matrix

$$\mathbf{w}_a = \left[\frac{t_{11} - t_{22} + \sqrt{(t_{11} - t_{22})^2 + 4|t_{12}|^2}}{2t_{12}^*} \quad 1 \quad 0 \right]^T$$

$$\mathbf{w}_b = \left[\frac{t_{11} - t_{22} - \sqrt{(t_{11} - t_{22})^2 + 4|t_{12}|^2}}{2t_{12}^*} \quad 1 \quad 0 \right]^T$$

$$\mathbf{w}_c = [0 \quad 0 \quad 1]^T$$

  - The third eigenvector can not be considered as it is also an eigenvector of the volume scattering matrix

- Estimation of the ground contribution necessary

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Cancelation of the Ground Component

Considering the RVoG coherent scattering model

$$\mathbf{T}_{11} = e^{-\frac{2\sigma h_v}{\cos\theta_0}} \begin{bmatrix} m_g\left(\frac{1}{\mu_s}+1\right) & m_g t_{12} & 0 \\ m_g t_{12}^* & m_g\left(\frac{\eta}{\mu_s}+t_{22}\right) & 0 \\ 0 & 0 & m_g\left(\frac{\eta}{\mu_s}+t_{33}\right) \end{bmatrix}$$

Assuming the Freeman-Durden decomposition for PolInSAR data

Ballester-Berman, J. & Lopez-Sanchez, J. "Applying the Freeman–Durden Decomposition Concept to Polarimetric SAR Interferometry," *IEEE TGRS,* vol. 48, pp. 466 -479, Jan. 2010

$$\hat{\mathbf{T}}_g = \begin{bmatrix} \mathbf{T}_{11}(1,1)-\frac{1}{\eta}\mathbf{T}_{11}(3,3) & \mathbf{T}_{11}(1,2) & 0 \\ \mathbf{T}_{11}(2,1) & \mathbf{T}_{11}(2,2)-\frac{1}{\eta}\mathbf{T}_{11}(3,3) & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

- The parameter η needs to be estimated from the data

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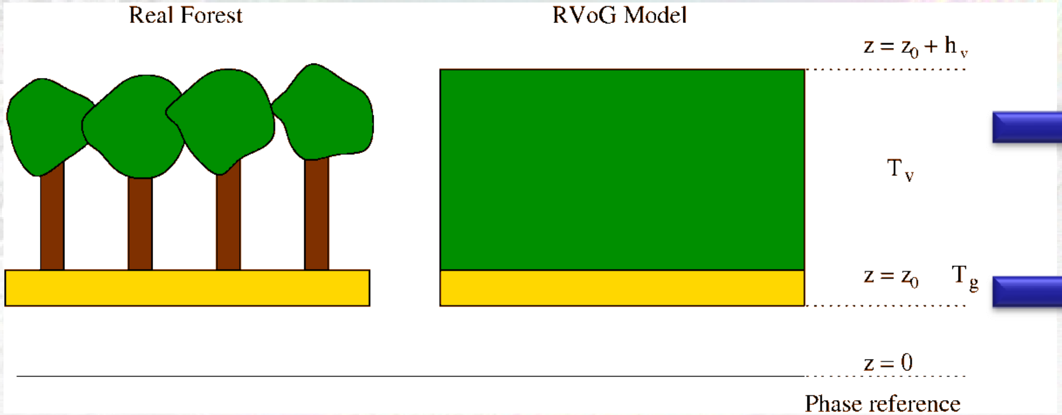
Simulated PolInSAR Data

esa

Underlying topography estimation: Simulated PolInSAR data

- Simulated scenario: Forest under the hypothesis of the RVoG model



Forest, η=0.25, σ=0.3 dB/m
Variable h_v

Flat, rough, loamy terrain, 2.2% water content (X-Bragg)
Variable ground phase

μ=-5 dB

- Imaging systems: DLR's E-SAR
  - Range spatial resolution 1.5 m
  - Azimuth spatial resolution 1.5 m
  - Wavelength λ=0.23 m (L-band)
  - Flight height H=3000 m
  - Mean incidence angle θ=45 deg
  - Horizontal baseline B=5 m
- Statistical distribution: Wishart pdf

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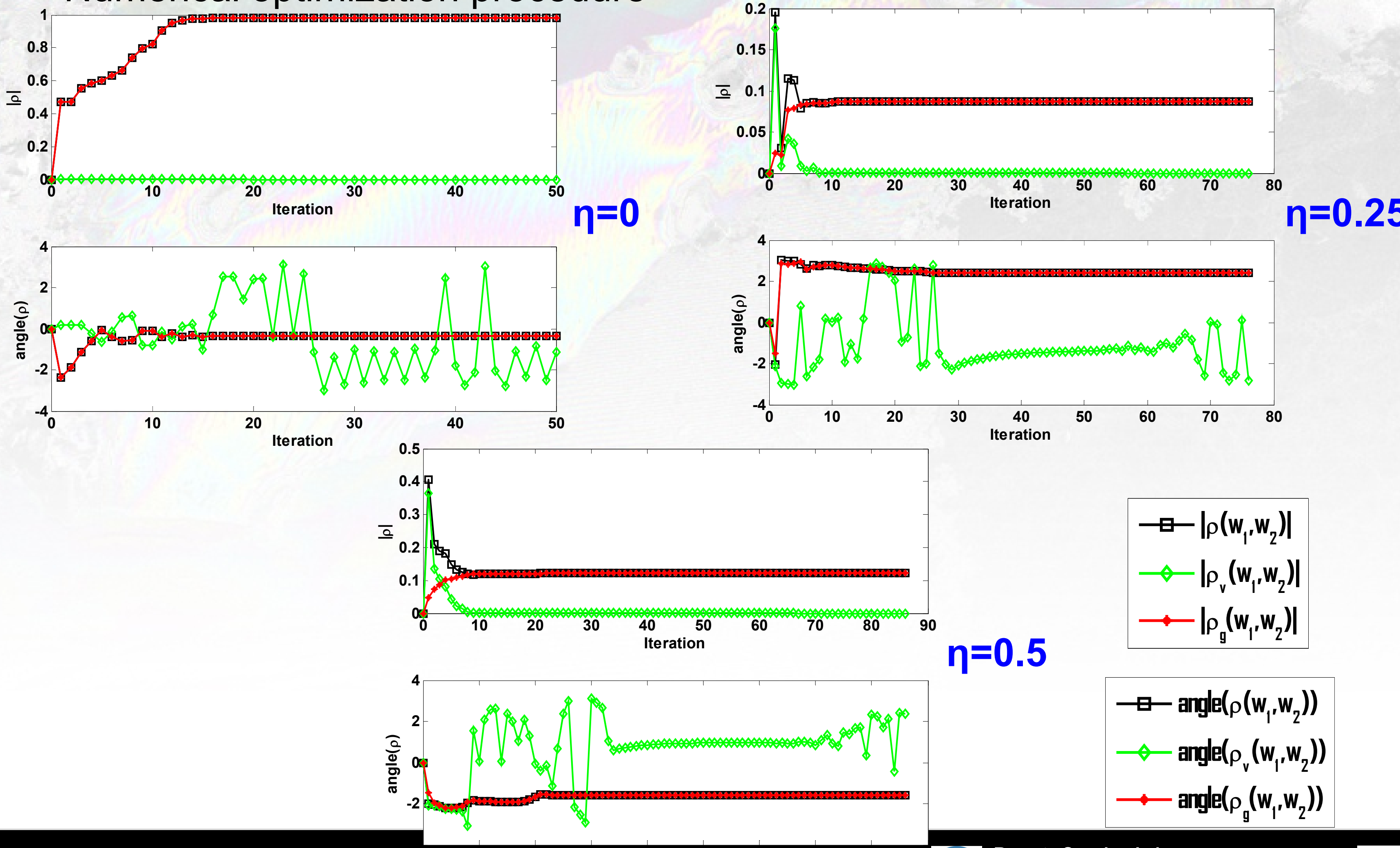
Validation

Cancelation of the volume coherence and optimization of the ground coherence

- Numerical optimization procedure



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Validation

Cancelation of the ground coherence

- The actual ground scattering matrix is considered
  - η is provided

	$\rho(\mathbf{w}_1,\mathbf{w}_2)$	$\rho_v(\mathbf{w}_1,\mathbf{w}_2)$	$\rho_g(\mathbf{w}_1,\mathbf{w}_2)$
$\eta = 0.1$	$0.437\triangleleft 2.542$	$0.437\triangleleft 2.542$	$1.42 \cdot 10^{-4}\triangleleft 3.141$
$\eta = 0.25$	$0.257\triangleleft 2.542$	$0.252\triangleleft 2.542$	$1.04 \cdot 10^{-4}\triangleleft 3.141$
$\eta = 0.5$	$0.126\triangleleft 2.542$	$0.126\triangleleft 2.542$	$7.68 \cdot 10^{-5}\triangleleft 3.141$

- The ground scattering matrix is estimated from data
  - η is provided

	$\rho(\mathbf{w}_1,\mathbf{w}_2)$	$\rho_v(\mathbf{w}_1,\mathbf{w}_2)$	$\rho_g(\mathbf{w}_1,\mathbf{w}_2)$
$\eta = 0.1$	$0.438\triangleleft 2.543$	$0.438\triangleleft 2.544$	$7.63 \cdot 10^{-4}\triangleleft 3.141$
$\eta = 0.25$	$0.258\triangleleft 2.542$	$0.258\triangleleft 2.542$	$1.79 \cdot 10^{-4}\triangleleft 3.141$
$\eta = 0.5$	$0.126\triangleleft 2.542$	$0.126\triangleleft 2.542$	$4.41 \cdot 10^{-5}\triangleleft 3.141$

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Phase Component Analysis

Volumetric and ground contributions have been separated, but the phase component of the remaining coherence terms presents polarimetric and interferometric contributions

$$\mathbf{\Omega}_{12} = e^{j\phi_1} e^{-\frac{2\sigma h_v}{\cos\theta_0}} \mathbf{\Omega}'_{12} = e^{j\phi_1} e^{-\frac{2\sigma h_v}{\cos\theta_0}} \begin{bmatrix} C_v m_v e^{j\Delta\phi} + m_g & m_g t_{12} & 0 \\ m_g t_{12}^* & C_v \eta m_v e^{j\Delta\phi} + m_g t_{22} & 0 \\ 0 & 0 & C_v \eta m_v e^{j\Delta\phi} + m_g t_{33} \end{bmatrix}$$

- Under the basis that $\mathbf{w}_1$ and $\mathbf{w}_2$ cancel the volume contribution of coherence

$$\arg\left\{\mathbf{w}_2^H \mathbf{\Omega}'_{12} \mathbf{w}_1\right\} = -\arg\left\{\mathbf{w}_1^H \mathbf{\Omega}'_{12} \mathbf{w}_2\right\}$$

- Under the basis that $\mathbf{w}_1$ and $\mathbf{w}_2$ cancel the ground contribution of coherence

$$\mathbf{w}_1^H \mathbf{\Omega}_{12} \mathbf{w}_2 = C_v\left(w_{11}^* w_{21} + \eta w_{12}^* w_{22} + \eta w_{13}^* w_{23}\right) = C_v w$$
$$\mathbf{w}_2^H \mathbf{\Omega}_{12} \mathbf{w}_1 = C_v\left(w_{21}^* w_{11} + \eta w_{22}^* w_{12} + \eta w_{23}^* w_{13}\right) = C_v w^*$$

These properties will allow to remove polarimetric information from phase

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Cancelation of the Volume Component

Assuming the cancelation of the volume contribution in coherence

$$\arg\left\{\mathbf{w}_1^H\mathbf{\Omega}_{12}\mathbf{w}_2\right\}=\arg\left\{e^{j\phi_1}e^{-\frac{2\sigma h_v}{\cos\theta_0}}\mathbf{w}_1^H\mathbf{\Omega}'_{12}\mathbf{w}_2\right\}=\phi_1+\arg\left\{\mathbf{w}_1^H\mathbf{\Omega}'_{12}\mathbf{w}_2\right\}$$

$$\arg\left\{\mathbf{w}_2^H\mathbf{\Omega}_{12}\mathbf{w}_1\right\}=\arg\left\{e^{j\phi_1}e^{-\frac{2\sigma h_v}{\cos\theta_0}}\mathbf{w}_2^H\mathbf{\Omega}'_{12}\mathbf{w}_1\right\}=\phi_1+\arg\left\{\mathbf{w}_2^H\mathbf{\Omega}'_{12}\mathbf{w}_1\right\}=\phi_1-\arg\left\{\mathbf{w}_1^H\mathbf{\Omega}'_{12}\mathbf{w}_2\right\}$$

A non-biased estimation of the underlying ground topography on vegetated areas is obtained through the analytical expression

$$\phi_1=\frac{1}{2}\arg\left\{\mathbf{w}_1^H\mathbf{\Omega}_{12}\mathbf{w}_2\cdot\mathbf{w}_2^H\mathbf{\Omega}_{12}\mathbf{w}_1\right\}$$

Generalization of previous results

- EUSAR 2010 (Aachen, Germany)

$$\phi_1=\frac{1}{2}\arg\left\{\mathbf{\Omega}_{12}(1,2)\mathbf{\Omega}_{12}(2,1)\right\}$$

- IGARSS 2010 (Honolulu, USA)

$$\phi_1=\arg\left\{\mathbf{\Omega}_{12}(1,2)\mathbf{T}_{11}(2,1)\right\}$$

C. López-Martínez and K. P. Papathanassiou, "Procedimiento para la estimación de la topografía de la superficie de la tierra en áreas con cobertura vegetal," Patent Request P201 000 793, June 16, 2010

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Cancelation of the Ground Component

Assuming the cancelation of the ground contribution in coherence

$$\mathbf{w}_1^H \mathbf{\Omega}_{12} \mathbf{w}_2 = C_v \left(w_{11}^* w_{21} + \eta w_{12}^* w_{22} + \eta w_{13}^* w_{23} \right) = C_v w$$

$$\mathbf{w}_2^H \mathbf{\Omega}_{12} \mathbf{w}_1 = C_v \left(w_{21}^* w_{11} + \eta w_{22}^* w_{12} + \eta w_{23}^* w_{13} \right) = C_v w^*$$

$$\rho_v \left(\mathbf{w}_1, \mathbf{w}_2 \right) = \frac{e^{j\phi_2} \mathbf{w}_1^H \mathbf{I}_2^v \mathbf{w}_2}{\sqrt{\mathbf{w}_1^H \left(\mathbf{I}_1^v + e^{-\frac{2\sigma h_v}{\cos\theta_0}} \mathbf{I}_1^g \right) \mathbf{w}_1 \mathbf{w}_2^H \left(\mathbf{I}_1^v + e^{-\frac{2\sigma h_v}{\cos\theta_0}} \mathbf{I}_1^g \right) \mathbf{w}_2}}$$

A non-biased estimation of the interferometric phase associated to the volume scattering center on vegetated areas is obtained through the analytical expression

$$e^{j2\phi_2} \mathbf{w}_1^H \mathbf{\Omega}_{12} \mathbf{w}_2 \cdot \mathbf{w}_2^H \mathbf{\Omega}_{12} \mathbf{w}_1 = e^{j2\phi_2} e^{-\frac{2\sigma h_v}{\cos\theta_0}} C_v^2 \left| w \right|^2$$

$$\arg\left\{ C_v \right\} = \frac{1}{2} \arg\left\{ e^{j2\phi_2} \mathbf{w}_1^H \mathbf{\Omega}_{12} \mathbf{w}_2 \cdot \mathbf{w}_2^H \mathbf{\Omega}_{12} \mathbf{w}_1 \right\} - \phi_2$$

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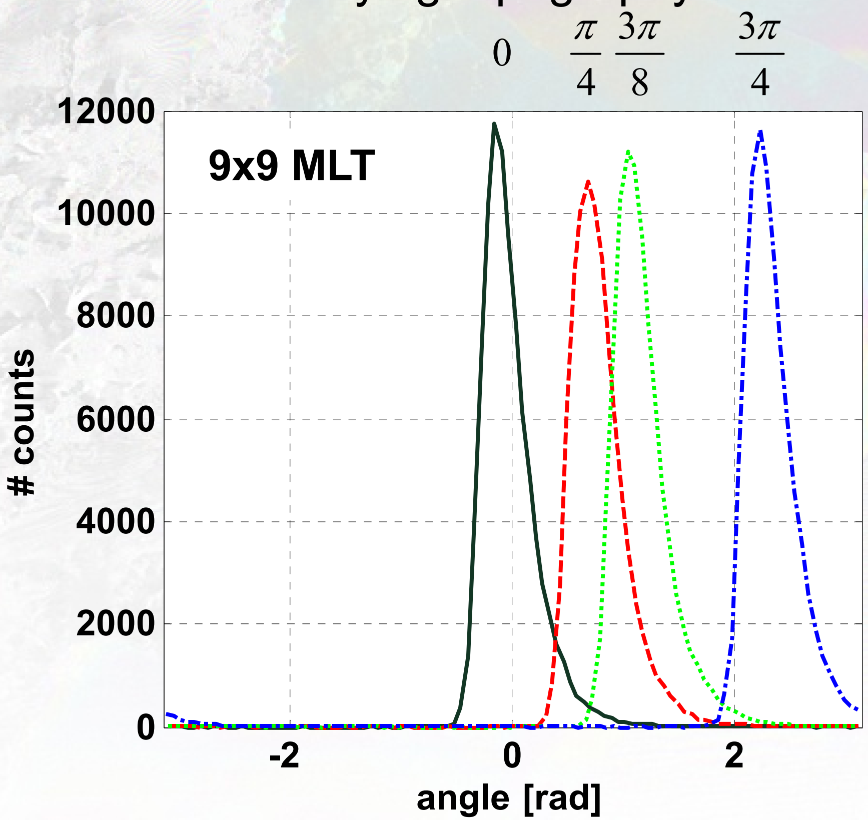
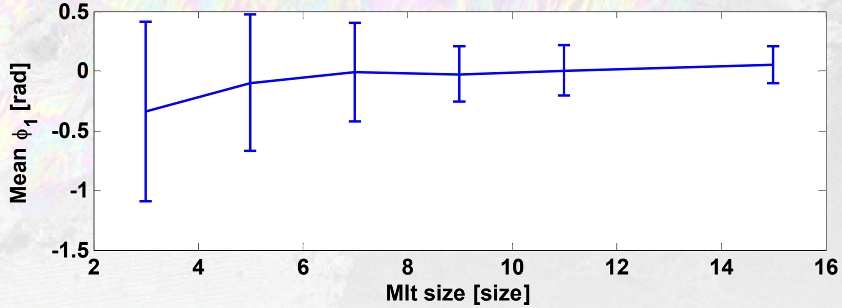
Validation Based on Simulated Data

Underlying topography estimation ϕ_1 considering **h_v=20 m** and **η=0.1**

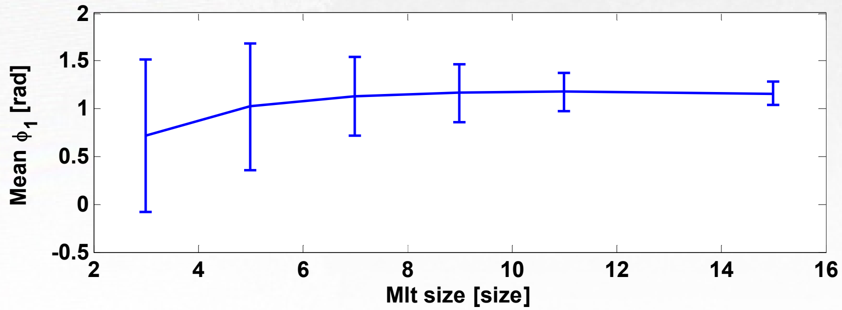


ϕ_1 rad	Mean estimated ϕ_1 rad	Std.Dev. estimated ϕ_1 rad
0	-0.028	0.230
$\pi/4$	0.770	0.250
$3\pi/8$	1.163	0.297
$3\pi/4$	2.262	0.682

Speckle noise effects



ϕ_1 =0 rad



ϕ_1 =3π/8 rad

Unbiased estimation of the ground topography on vegetated areas

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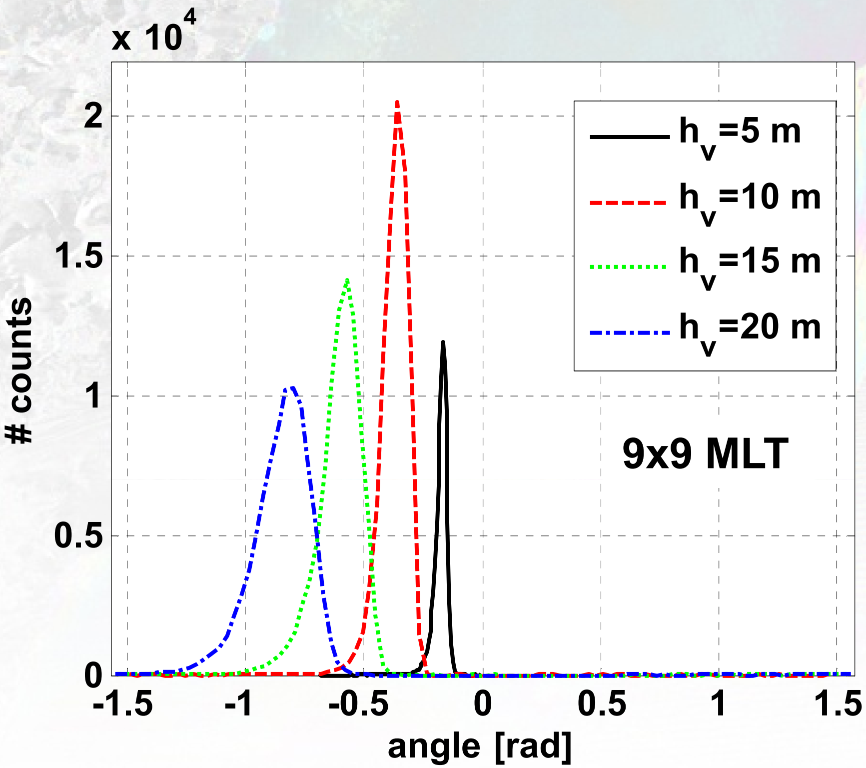
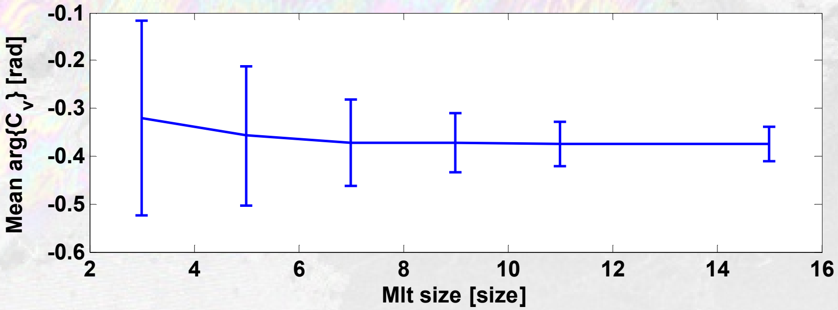
Validation Based on Simulated Data

Estimation of the interferometric phase associated to the volumetric scattering center $\arg\{C_v\}$ and **η=0.1**

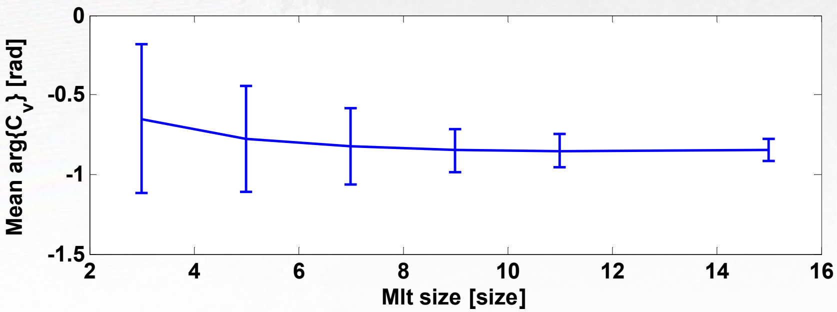


h_v m	$\arg\{C_v\}$ rad	Mean estimated $\arg\{C_v\}$ rad	Std.Dev. estimated $\arg\{C_v\}$ rad
5	-0.174	-0.174	0.028
10	-0.374	-0.372	0.062
15	-0.549	-0.605	0.108
20	-0.846	-0.849	0.137

Speckle noise effects



h_v =10 m



h_v =20 m

Unbiased estimation of the volumetric scattering center phase

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Results: Experimental PolInSAR Data

Underlying topography estimation: P-band experimental PolInSAR data

- INDREX-II campaign Oct-Dec 2004
- Observation system: DLR E-SAR
  - P-band data
  - Spatial baselines B: 15 m, 30 m
  - Temporal baselines T: 20 min, 40 min
- Tropical forest
  - Mawas-E site, Central Kalimantan, Indonesia
  - Flat area
  - Tropical peat swamp forest types
  - Biomass range: 50-400 ton/ha
  - Height range: 5-25 m

Pauli RGC decomposition of the master data set |HH+VV| |HV| |HH-VV|

Aerial photograph

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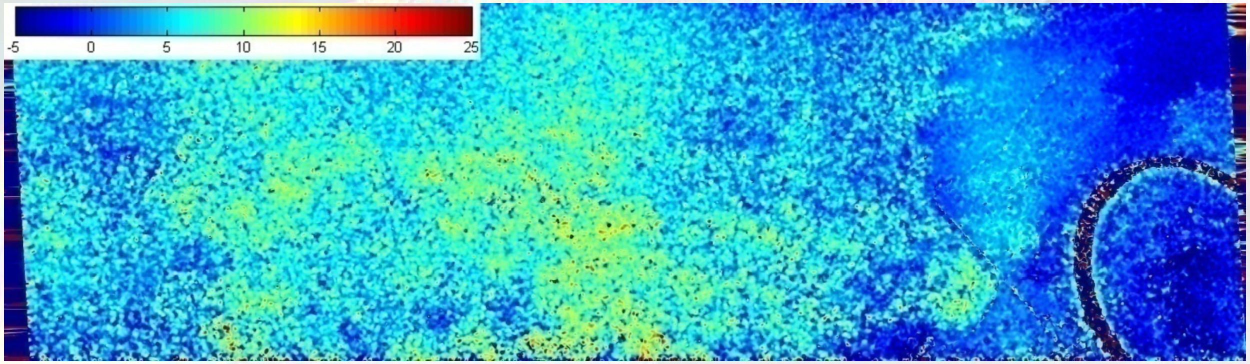
Results: Experimental PolInSAR Data

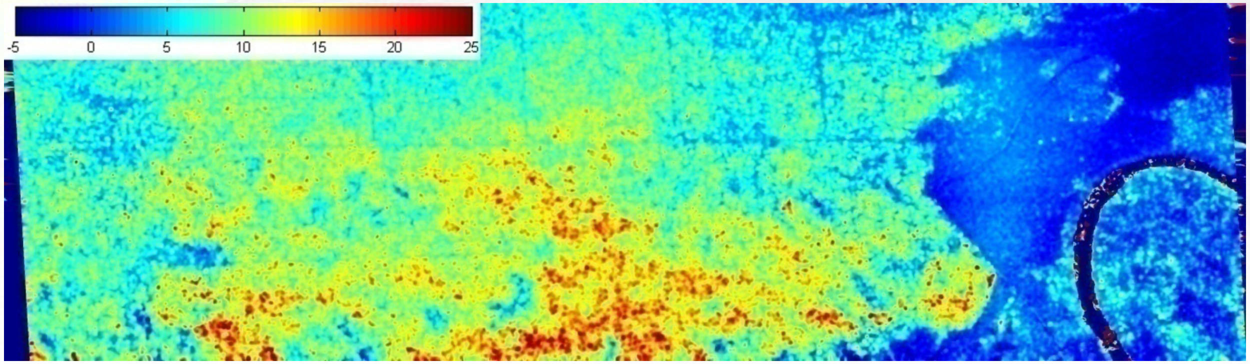
Dataset: P-band, **B=15 m**

- Transformation to height [m] information included (κ_z)

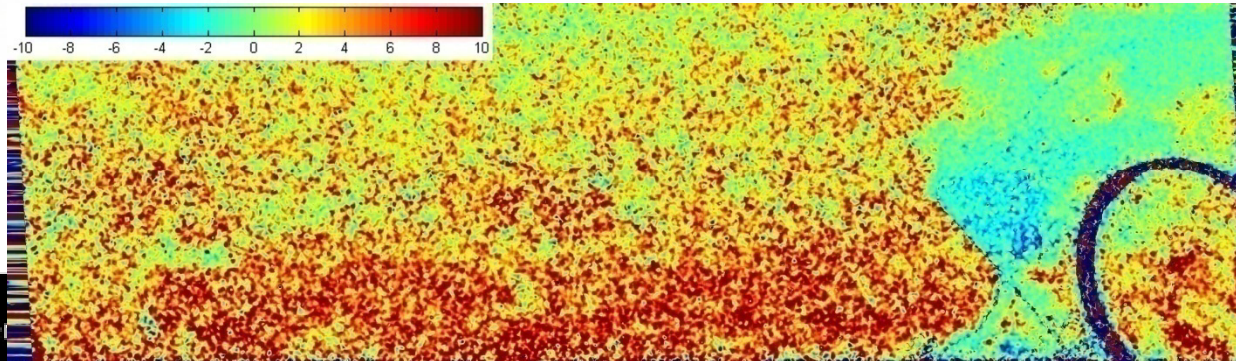
Height retrieved from ϕ_1



Phase center height retrieved from $\langle S_{hv,1} S^*_{hv,2} \rangle$



Height difference

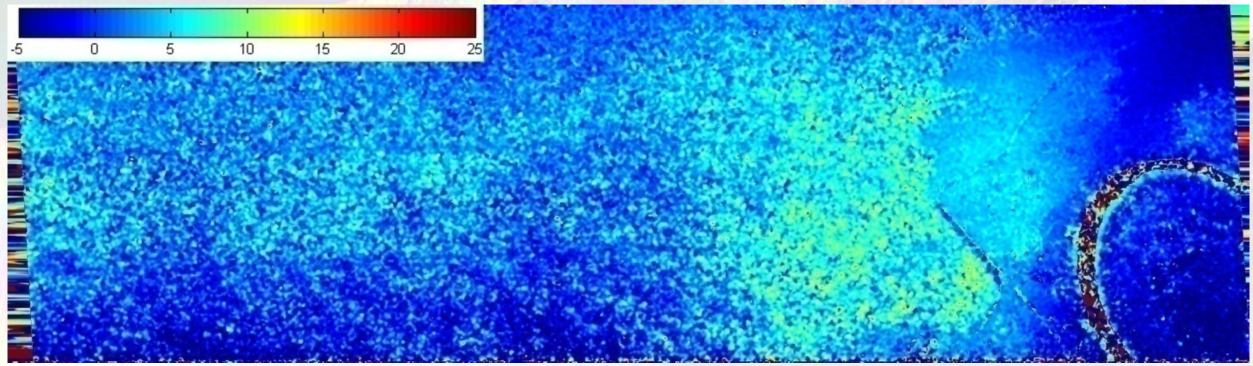


Results: Experimental PolInSAR Data

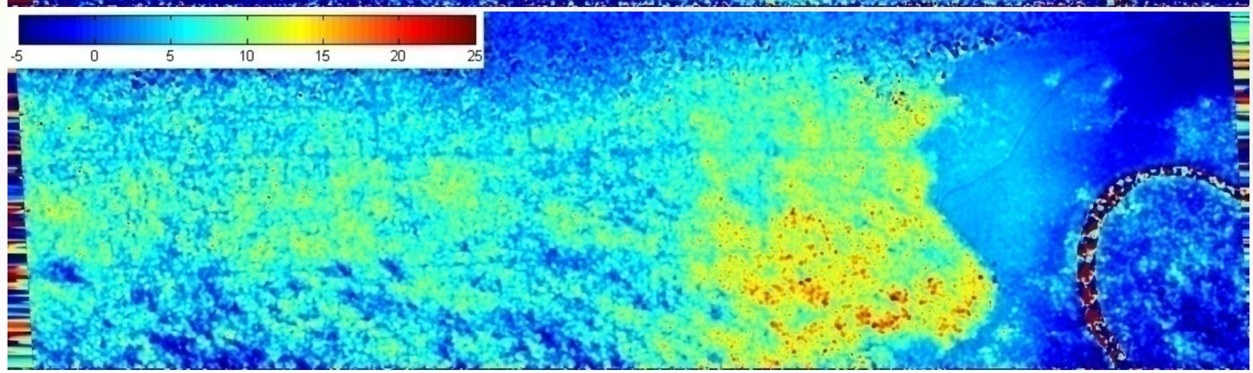
Dataset: P-band, **B=30 m**

- Transformation to height [m] information included (κ_z)

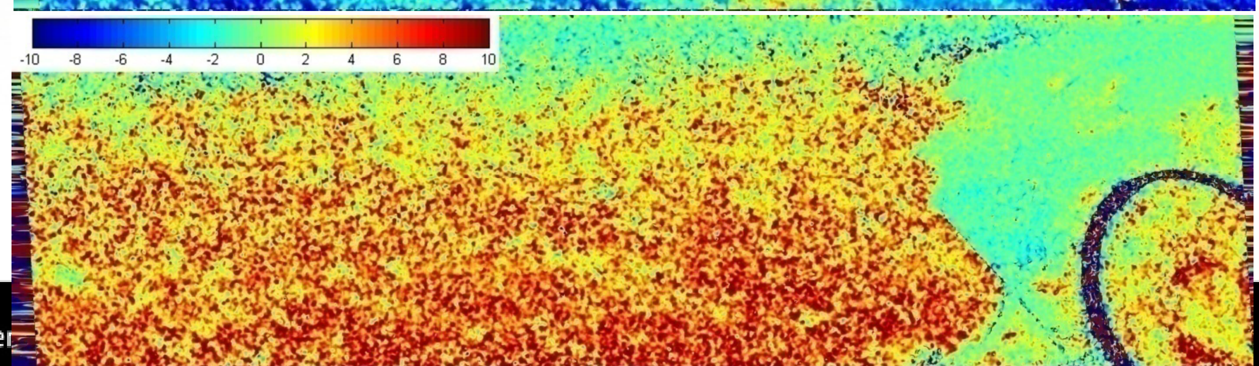
Height retrieved from ϕ_1



Phase center height retrieved from $\langle S_{hv,1} S^*_{hv,2} \rangle$



Height difference

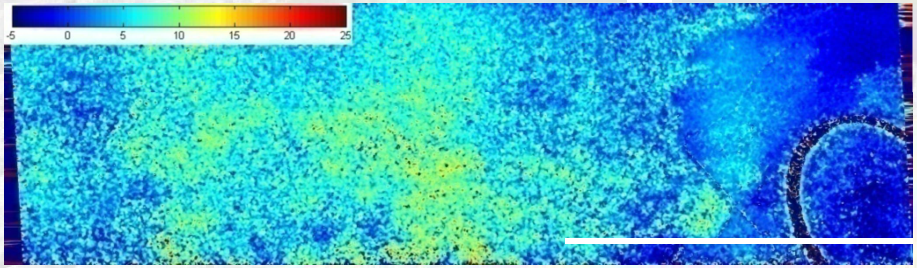


Results: Experimental PolInSAR Data

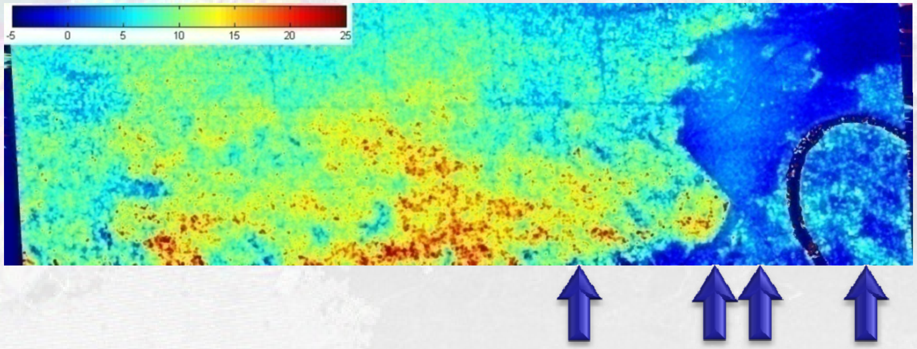
Underlying topography estimation: Absolute height analysis

B = 15 m

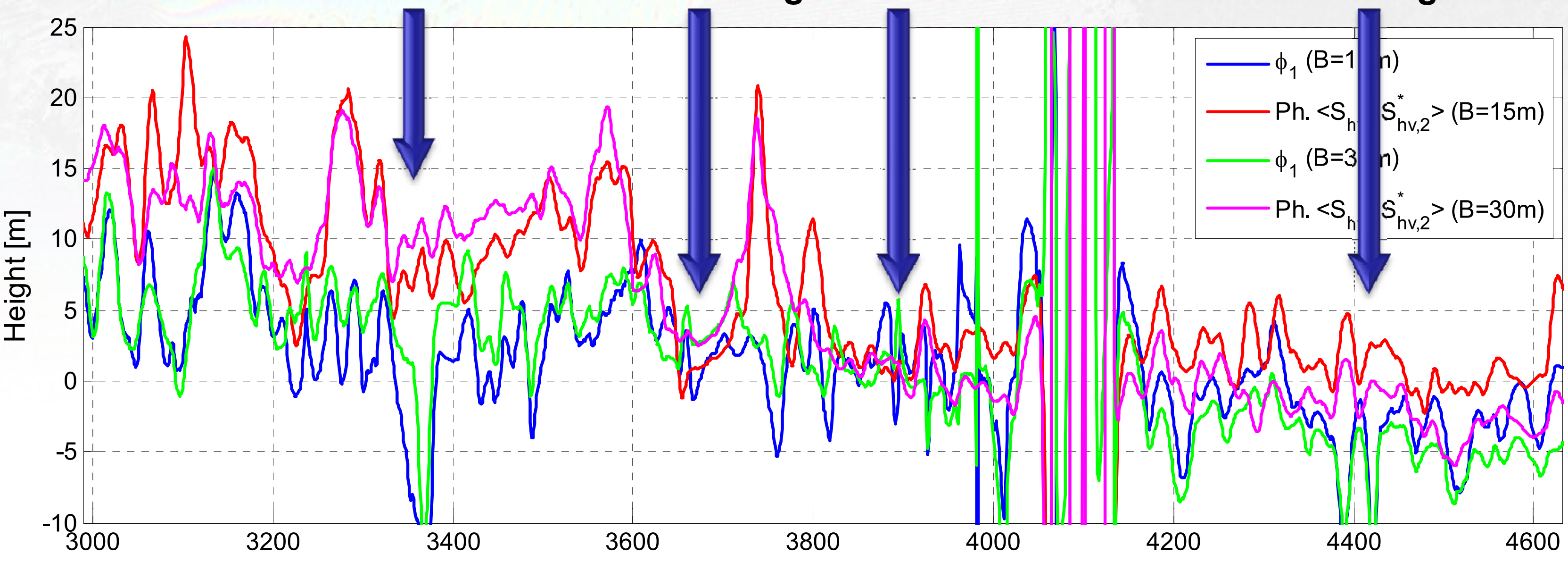
Height retrieved from ϕ_1



Height retrieved from $\langle S_{hv,1} S^*_{hv,2} \rangle$



Forest **Un-vegetated** **Forest/Low vegetation**



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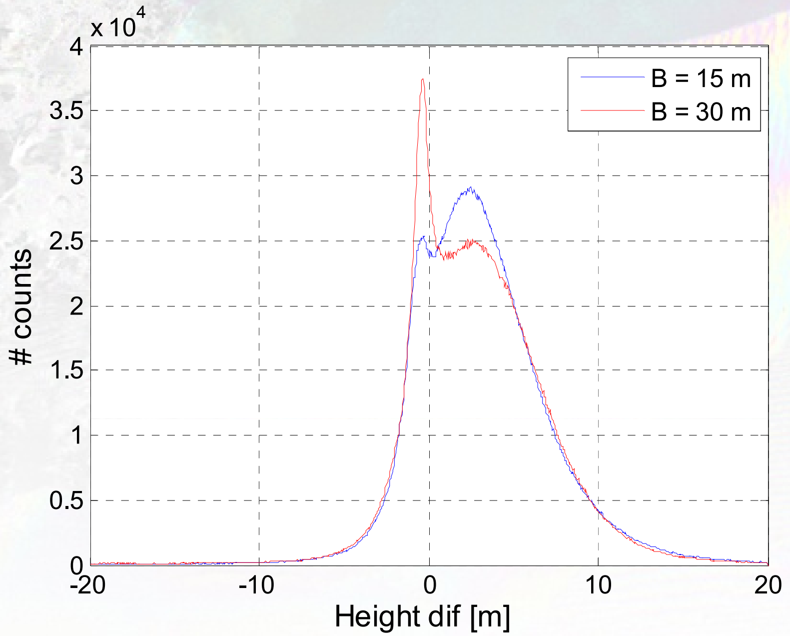
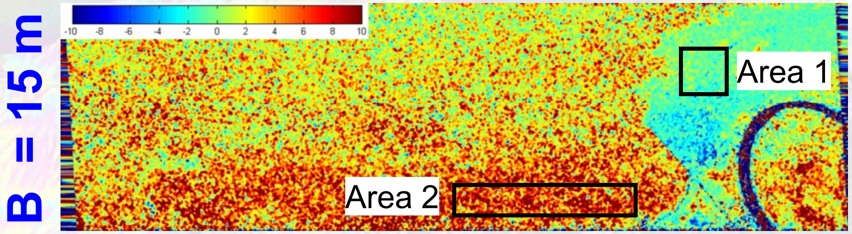
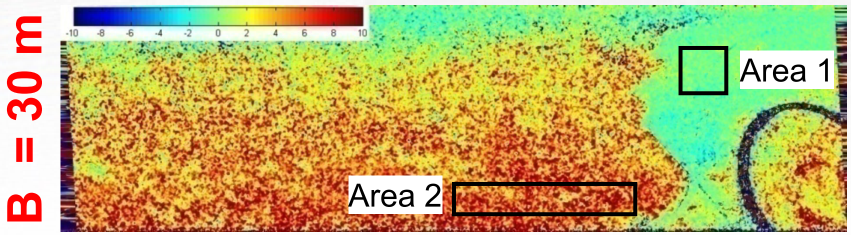
Results: Experimental PolInSAR Data

Underlying topography estimation: Height difference analysis





- Area 1 mean value = - 0.57 m
- Area 2 mean value = 7.48 m



- Area 1 mean value = - 0.32 m
- Area 2 mean value = 6.83 m

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Conclusions

- Extended analysis of the RVoG coherent scattering model for forested areas characterization

- Use of orthogonal scattering mechanisms allows to separate different polarimetric scattering mechanisms
  - Low coherence problem

- Products of interferograms allow to separate interferometric from polarimetric information

- Direct, unbiased & unambiguous estimation of the underlying topography
  - Analytical expression for the underlying topography
  - Asymptotically unbiased estimation from an stochastic point of view
- Direct & unbiased estimation of the volumetric scattering center height
  - Depends on the ground topography estimation
  - Asymptotically unbiased estimation from an stochastic point of view

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