Ecological applications with repeat-pass Pol-InSAR

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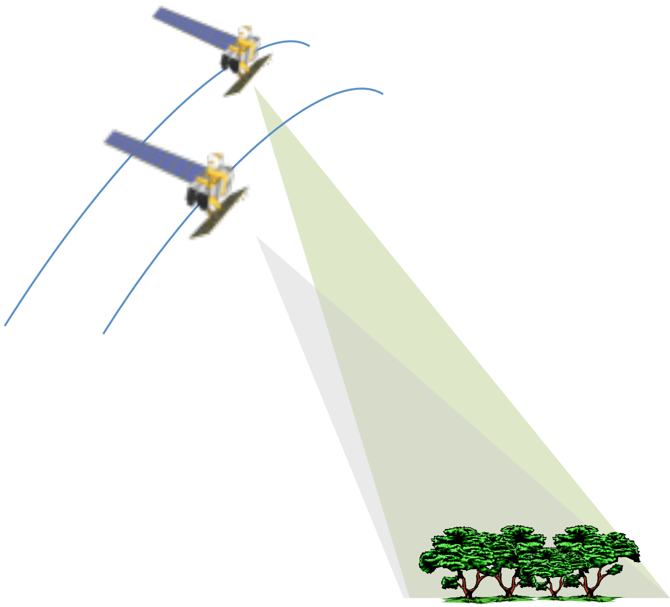
Outline

- Introduction and motivation
- Part I: The RMoG model
  - Modeling assumptions
  - Consequences of the RMoG model
- Part II: Inversion of the RMoG model
  - Inversion using single-baseline Pol-InSAR data
  - Numerical simulations
  - UAVSAR experiments

Background

- Cancellation of DESDynI lidar motivated us to look for alternative approaches for ecosystem science
- DESDynI Science Steering Group and broader ESWG recognize the potential of Pol-InSAR
- Terrestrial Ecology funded Pol-InSAR algorithm development and field experiments
- NASA CCE workshop in Oct 2011 addressed the problem of temporal decorrelation

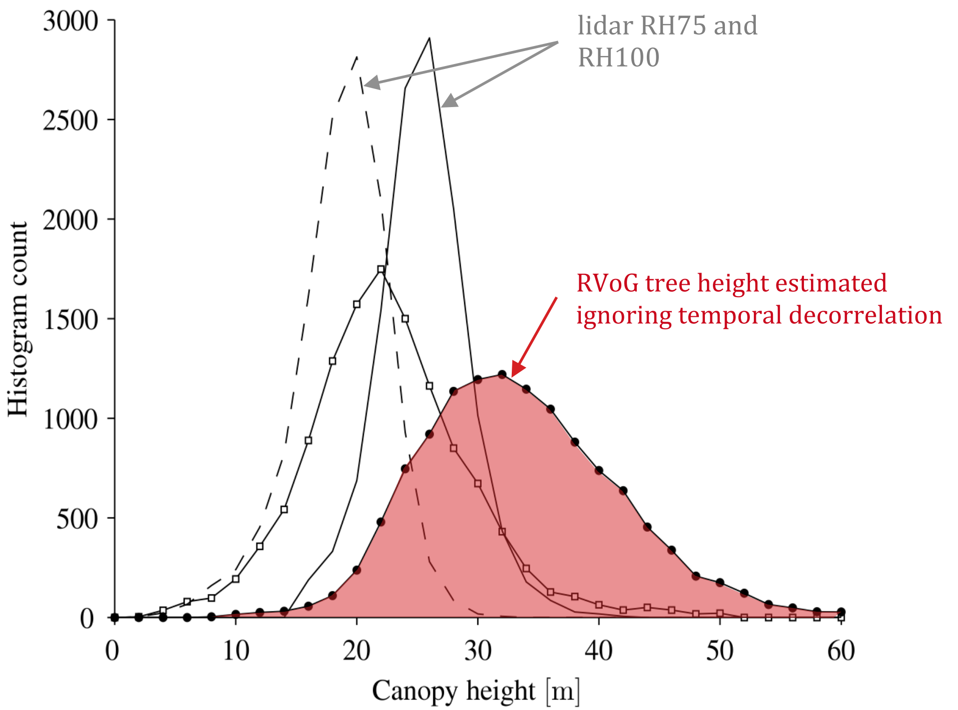
polarimetric radar interferometer (Pol-InSAR)



Motivation and objectives

- Current and forthcoming low-frequency SAR missions (ALOS-1/2, BIOMASS, DESDynI) collect repeat-pass data
- The use of repeat-pass Pol-InSAR data is predicated on solving/mitigating the problem of temporal decorrelation
- Objective is to provide a model-based algorithm that "compensates for" temporal decorrelation while forest parameter are estimated

Canopy height estimated from 2-day repeat-pass JPL/UAVSAR data (Harvard Forest, MA)



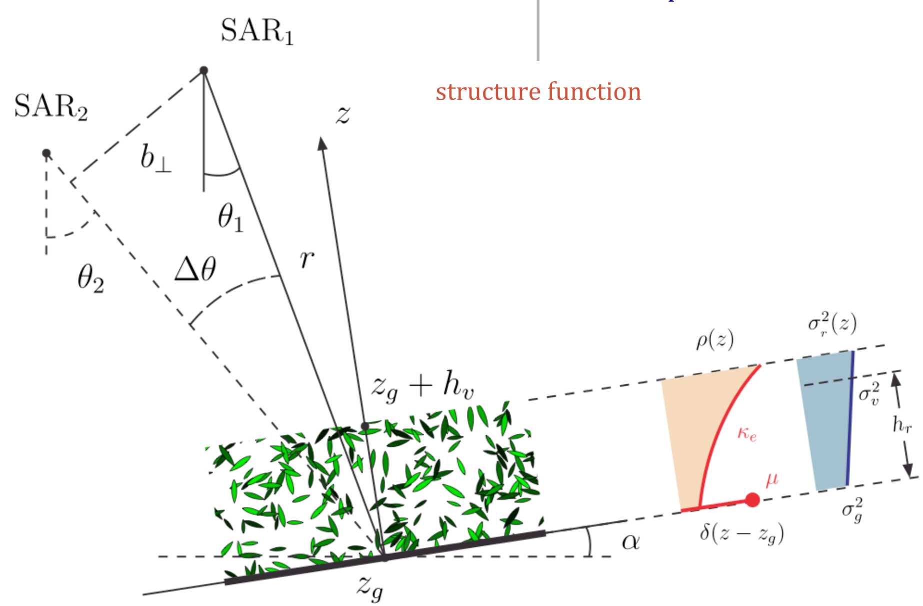
The RMoG model

$$\gamma = \frac{\int \rho(z)\, e^{j k_z z} \exp\left[-\frac{1}{2}\left(\frac{4\pi}{\lambda}\right)^2 \sigma_r^2(z)\right] \mathrm{d}z}{\int \rho(z)\, \mathrm{d}z}$$

temporal function

structure function

- Random-motion-over-ground (RMoG) model: RVoG model + refined Zebker's model
- Physical model of temporal-volumetric coherence proposed in late 2009 and improved throughout 2010-2012
- Exponential structure function for volumetric decorrelation
- First-order expansion of arbitrary temporal function for temporal decorrelation (time-dependence dropped)



Key properties of the RMoG model

- 4 structural + 2 temporal = 6 model parameters
- Temporal and volumetric decorrelations are mixed and not separable

RMoG coherence

$$\gamma = e^{j\varphi_g} \frac{\mu \gamma_{t_g} + \gamma_{vt} e^{-j\varphi_g}}{\mu + 1} \qquad \gamma \neq \gamma_t \gamma_v$$

ground-layer coherence

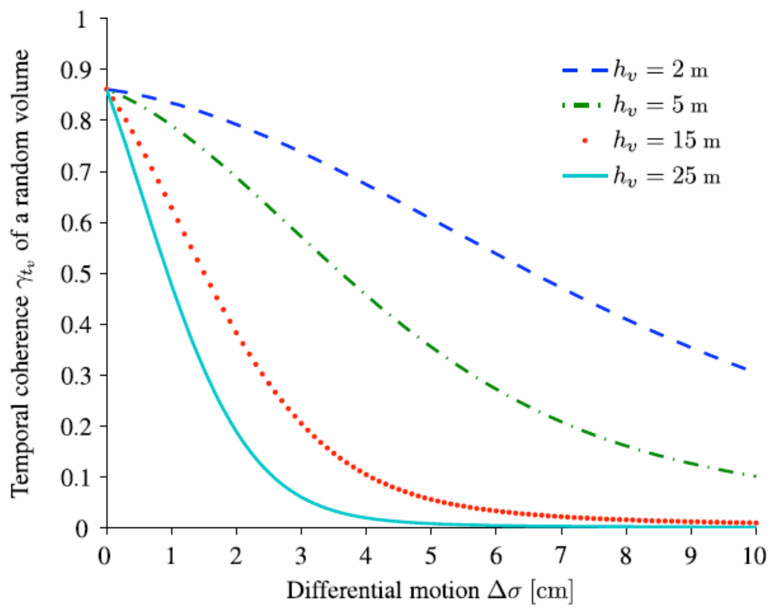
$$\gamma_{t_g} = \exp\left[-\frac{1}{2}\left(\frac{4\pi}{\lambda}\right)^2 \sigma_g^2\right]$$

canopy-layer coherence

$$\gamma_{vt} = e^{j\varphi_g} \gamma_{t_g} \frac{p_1 \left[e^{(p_2+p_3)h_v} - 1\right]}{(p_2+p_3)\left(e^{p_1 h_v} - 1\right)}$$

property n. 1

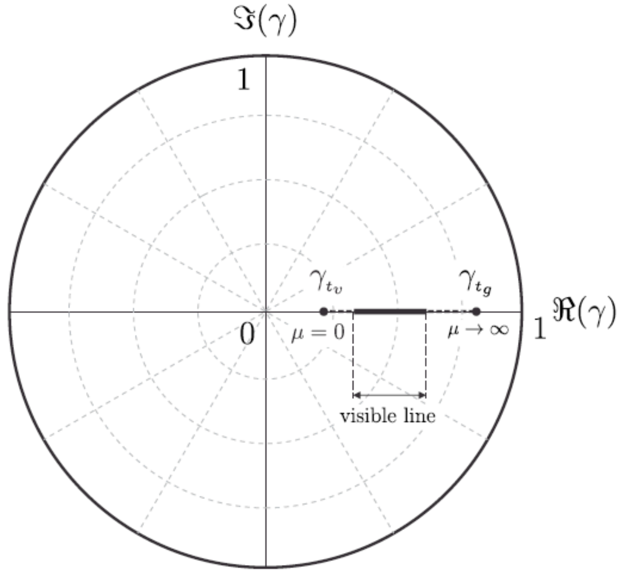
RMoG temporal decorrelation depends on vegetation structure (e.g. canopy height)



$$p_1 = \frac{2\kappa_e}{\cos(\theta - \alpha)}, \qquad p_2 = p_1 + jk_z, \qquad p_3 = -\frac{\Delta\sigma^2}{2h_r}\left(\frac{4\pi}{\lambda}\right)^2$$

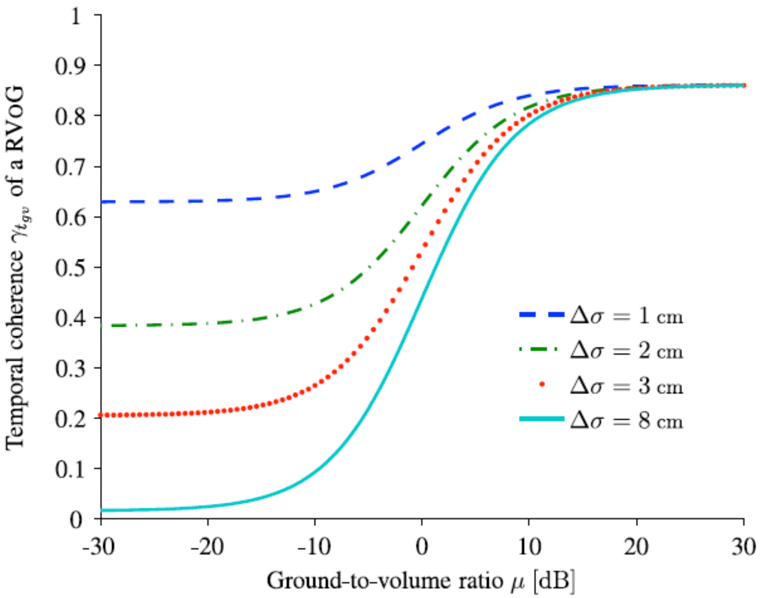
Key properties of the RMoG model

Coherence locus of RMoG temporal decorrelation



property n. 2

RMoG temporal decorrelation depends on wave polarization through the ground-to-volume ratio



M. Lavalle, M. Simard and S. Hensley, "A temporal decorrelation model for polarimetric radar interferometers", IEEE TGRS 2012.

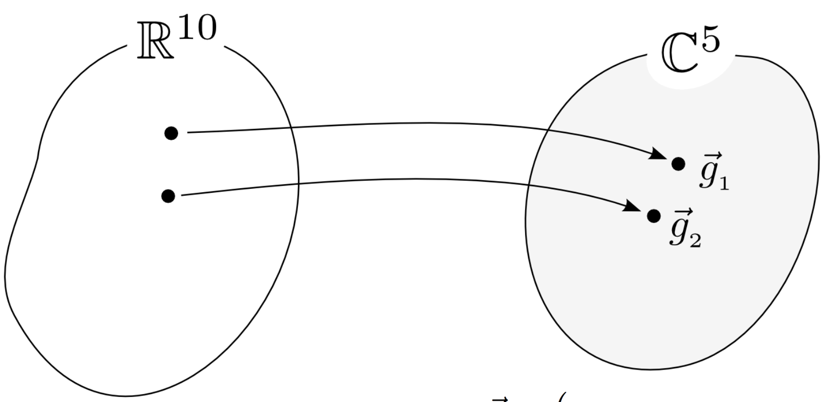
Part II
Inversion of the RMoG model

From RMoG model to RMoG forward problem

- RMoG forward problem formulated as mapping of ten-dimensional real vector into five-dimensional complex vector
- Each coherence observation has a different ground-to-volume ratio
- Domain of RMoG forward problem is a subset of the 10-dimensional real space
- Codomain of RMoG forward problem is a subset of the 5-dimensional complex space

$$f : \begin{pmatrix} \varphi_g \\ h_v \\ \kappa_e \\ \sigma_g \\ \sigma_v \\ \mu_1 \\ \mu_2 \\ \mu_3 \\ \mu_4 \\ \mu_5 \end{pmatrix} \longmapsto \begin{pmatrix} \gamma_1 \\ \gamma_2 \\ \gamma_3 \\ \gamma_4 \\ \gamma_5 \end{pmatrix}$$

$$f \, : \, U \subset \mathbb{R}^{10} \longrightarrow V \subset \mathbb{C}^5$$



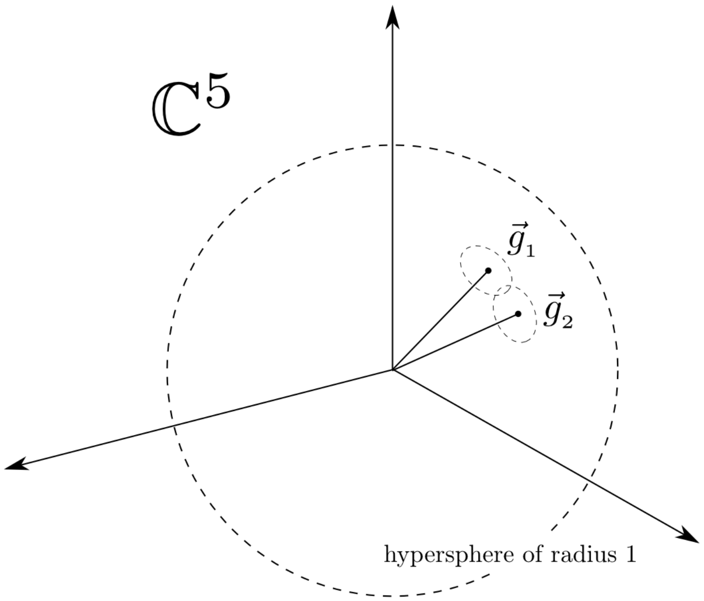
$$\vec{g} = (\gamma_1, \gamma_2, \gamma_3, \gamma_4, \gamma_5)^T$$

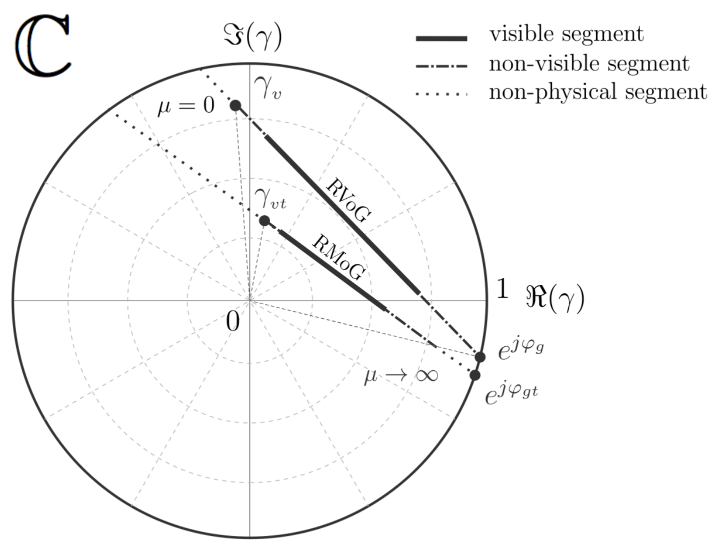
K. Papathanassiou and S. Cloude, "Single-Baseline Polarimetric SAR Interferometry," TGRS, vol. 39, no. 11, pp. 2352–2363, 2001.

I. Hajnsek et Al., "Tropical-Forest-Parameter Estimation by Means of Pol-InSAR: The INDREX-II Campaign," TGRS, vol. 47, no. 2, pp. 481 –493, Feb. 2009.

RMoG inverse problem

- The codomain of the RMoG forward problem is not the coherence locus
- Two coherence observations are sufficient to estimate the coherence locus, but not the RMoG model parameters
- Values of RMoG model parameters are inferred from vector of observations
- The RMoG forward problem is ambiguous if two vectors of model parameters map in the same coherence vector





RMoG inversion strategy

1. Coherence phase optimization → end points of visible line
2. Unit circle intersection → approximate ground phase
3. Constrained least-square optimization of non-linear, complex problem using interior-point algorithm and analytically-derived gradient

$$
\begin{cases}
\widehat{\gamma}_1 e^{-j\varphi_{gt}} & = & e^{j(\varphi_g-\varphi_{gt})} \dfrac{\mu_1 \gamma_{t_g} + \gamma_{vt} e^{-j\varphi_g}}{\mu_1 + 1} \\
\widehat{\gamma}_2 e^{-j\varphi_{gt}} & = & e^{j(\varphi_g-\varphi_{gt})} \dfrac{\mu_2 \gamma_{t_g} + \gamma_{vt} e^{-j\varphi_g}}{\mu_2 + 1} \\
\widehat{\gamma}_3 e^{-j\varphi_{gt}} & = & e^{j(\varphi_g-\varphi_{gt})} \dfrac{\mu_3 \gamma_{t_g} + \gamma_{vt} e^{-j\varphi_g}}{\mu_3 + 1} \\
\widehat{\gamma}_4 e^{-j\varphi_{gt}} & = & e^{j(\varphi_g-\varphi_{gt})} \dfrac{\mu_4 \gamma_{t_g} + \gamma_{vt} e^{-j\varphi_g}}{\mu_4 + 1} \\
\widehat{\gamma}_5 e^{-j\varphi_{gt}} & = & e^{j(\varphi_g-\varphi_{gt})} \dfrac{\mu_5 \gamma_{t_g} + \gamma_{vt} e^{-j\varphi_g}}{\mu_5 + 1}
\end{cases}
$$

$$F = \sum_{i=1}^{5} \left| \gamma_i - \widehat{\gamma}_i \right|^2$$

$$\gamma_i = e^{j\varphi_g} \frac{\mu_i \gamma_{t_g} + \gamma_{vt} e^{-j\varphi_g}}{\mu_i + 1}$$

$$\widehat{\gamma}_i = \widehat{\gamma}_1 + F_i \left(e^{j\varphi_{gt}} - \widehat{\gamma}_1 \right), \quad F_i = \frac{F_5}{4}(i-1)$$

$$\sigma_v \geq \sigma_g$$

$$\nabla f = \begin{pmatrix} \partial\gamma/\partial\varphi_g \\ \partial\gamma/\partial h_v \\ \partial\gamma/\partial\kappa_e \\ \partial\gamma/\partial\sigma_g \\ \partial\gamma/\partial\sigma_v \\ \partial\gamma/\partial\mu_1 \\ \partial\gamma/\partial\mu_2 \\ \partial\gamma/\partial\mu_3 \\ \partial\gamma/\partial\mu_4 \\ \partial\gamma/\partial\mu_5 \end{pmatrix}$$

M. Lavalle and S. Hensley, "Repeat-pass Polarimetric SAR Interferometry", IEEE TGRS 2013 (in review).

RMoG inversion: Existence and uniqueness of the solution

RMoG numerical simulations

- large range of model parameters

  $\varphi_g \in [-\pi,\ \pi]\,\mathrm{rad}$

  $h_v \in [0,\ 30]\,\mathrm{m}$

  $\kappa_e \in [0.1,\ 0.3]\,\mathrm{dB\,m^{-1}}$

  $\sigma_g = 0\,\mathrm{cm}$

  $\sigma_v = 0\,\mathrm{cm}$

  $\mu_{\max} \in [0,\ 10]\,\mathrm{dB}$

  $\mu_{\min} \in [-10,\ -30]\,\mathrm{dB}$

- UAVSAR radar and acquisition geometry

  $k_z = 0.12\,\mathrm{m^{-1}}$

  $\lambda = 0.2384\,\mathrm{m}$

  $\theta = 45\ \mathrm{deg}$

- 300 RMoG coherence simulations and RMoG inversions

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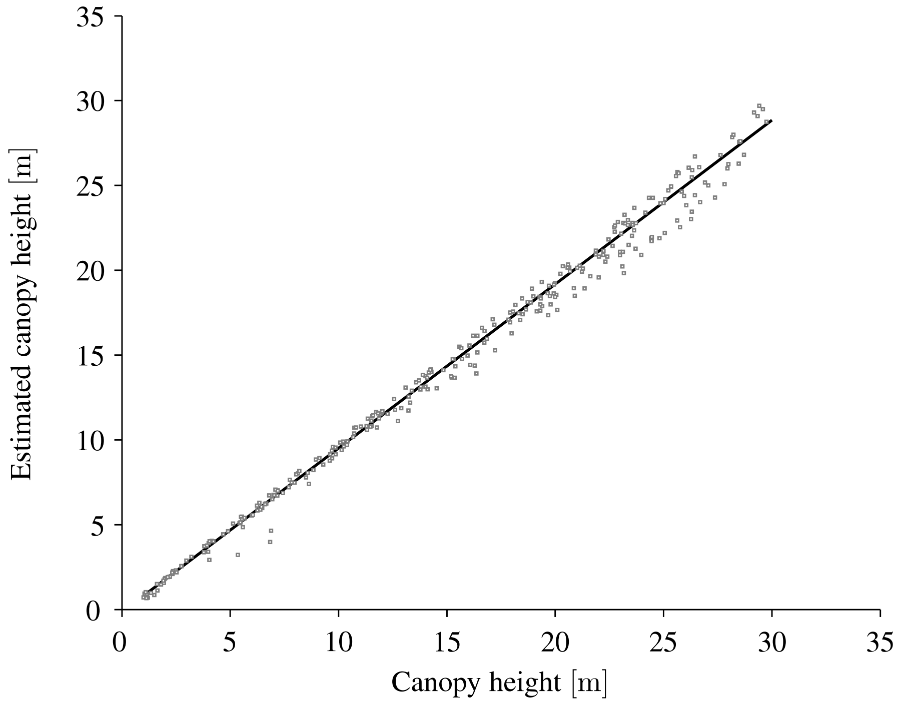

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  $h_v \in [0,\ 30]$ m
  $\kappa_e \in [0.1,\ 0.3]\ \mathrm{dB\,m^{-1}}$
  $\sigma_g \in [0,\ 1]$ cm $\quad (\gamma_t \simeq 0.87)$
  $\sigma_v \in [1,\ 2]$ cm $\quad (\gamma_t \simeq 0.57)$
  $\mu_{\max} \in [0,\ 10]$ dB
  $\mu_{\min} \in [-10,\ -30]$ dB

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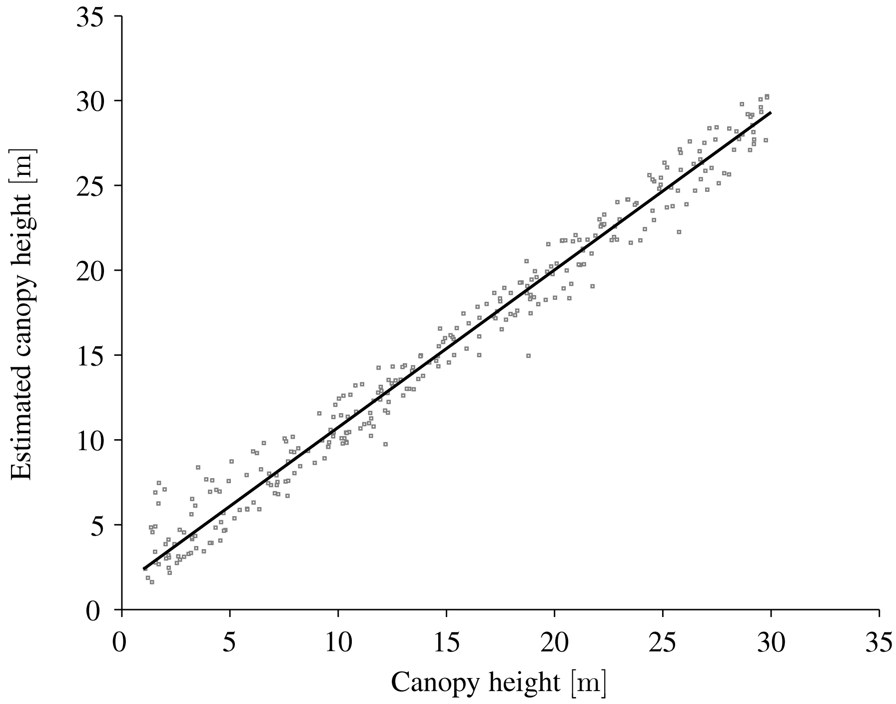
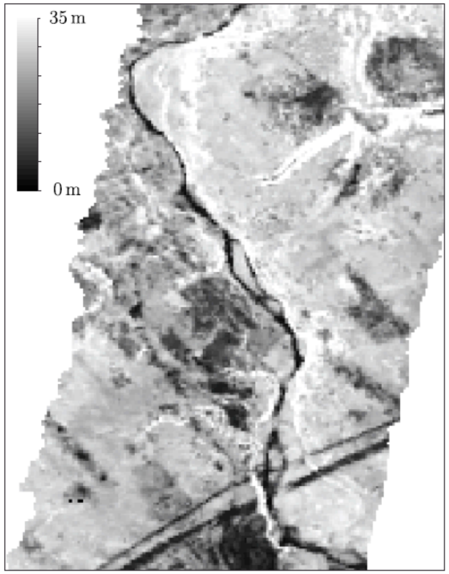


RMoG model VS real world: UAVSAR experiments

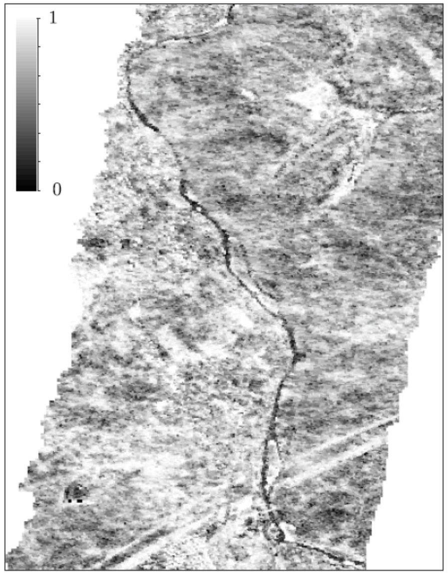
Validation of temporal decorrelation model ($b_{\perp} = 0$)

Quebec (Canada); 45 min temporal interval; ~zero vertical wavenumber; L-band UAVSAR

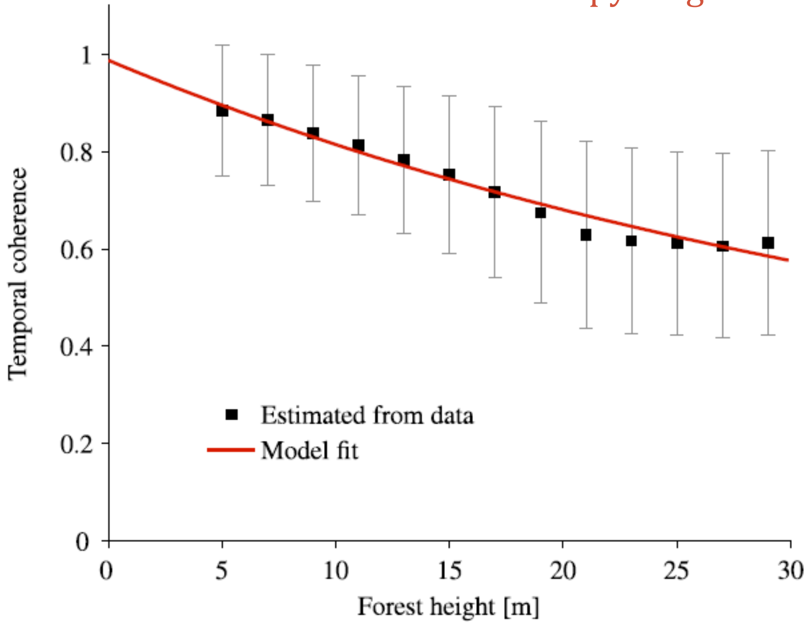
LVIS lidar canopy height



UAVSAR HV-coherence ($\mu \approx 0$)



validation of dependence of temporal decorrelation on canopy height



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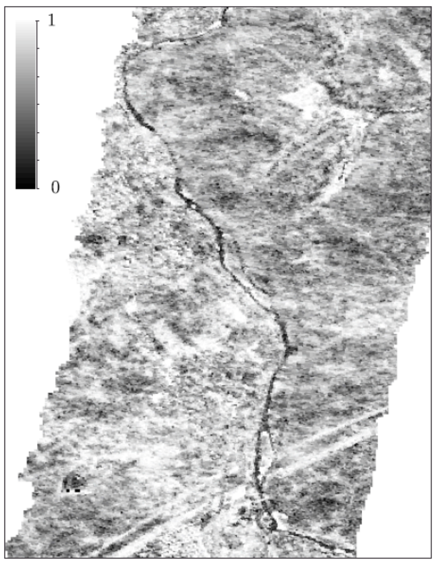
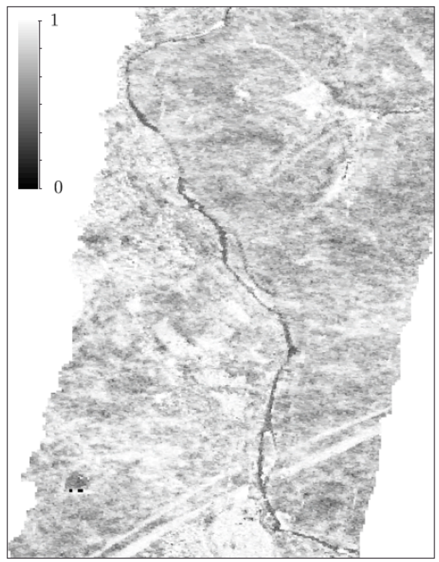
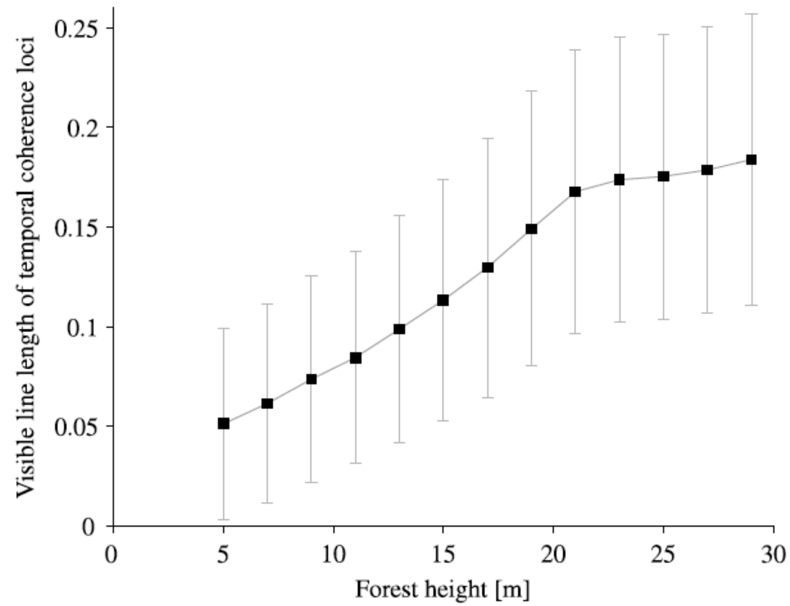


optimized high coherence



validation of dependence of temporal correlation on wave polarization



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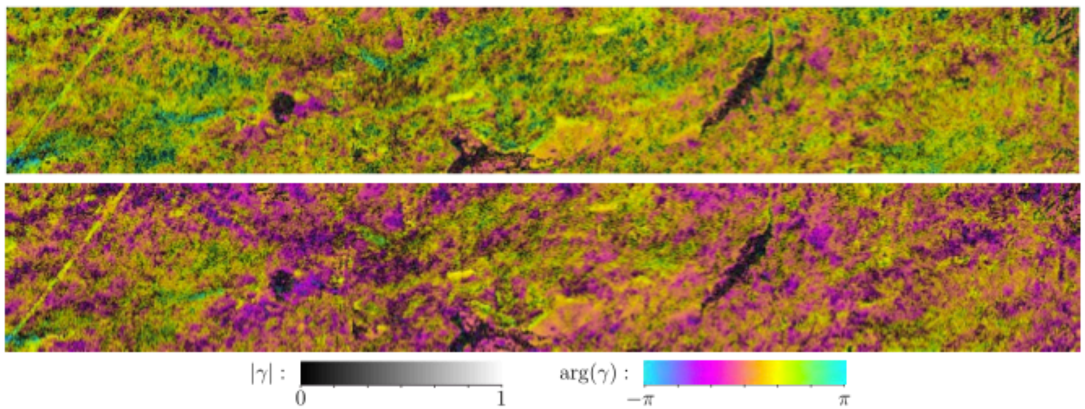
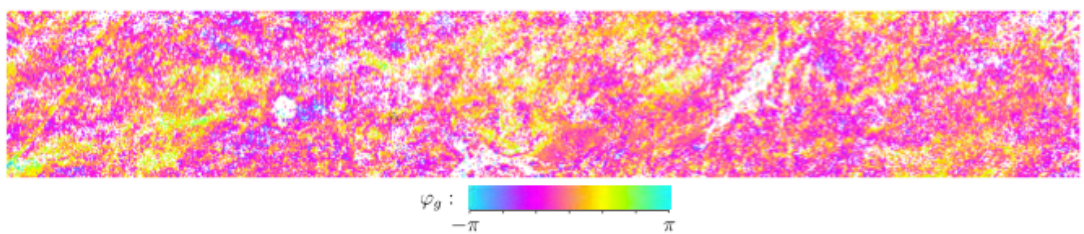
Tree height from Pol-InSAR UAVSAR data

Harvard Forest, MA (US); 2 days temporal interval; 0.075 m^{-1} vertical wavenumber; L-band

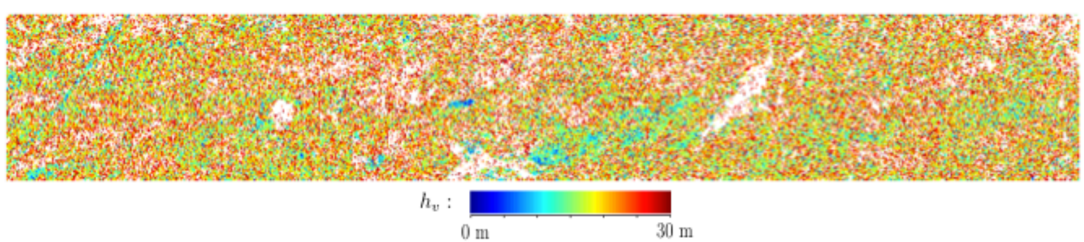


Canopy-dominated coherence

Ground-dominated coherence



Estimated ground topography



Estimated canopy height

Tree height from Pol-InSAR UAVSAR data VS lidar LVIS

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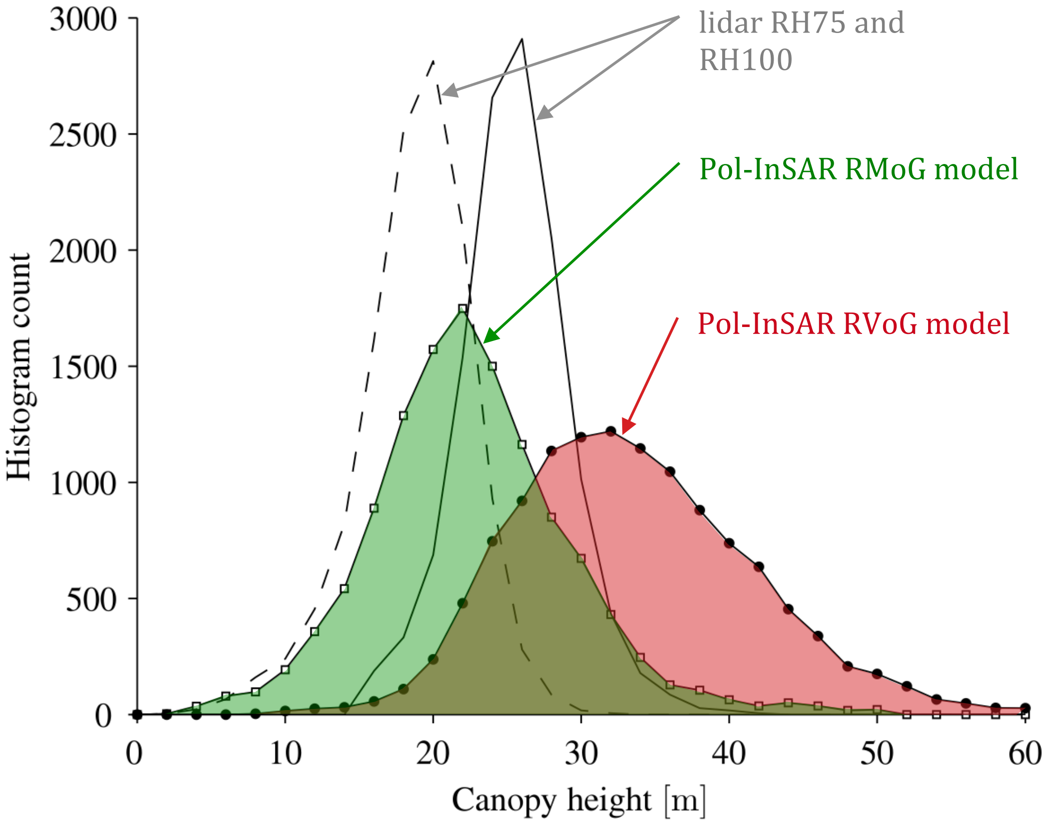

RMoG temporal parameters from Pol-InSAR UAVSAR data

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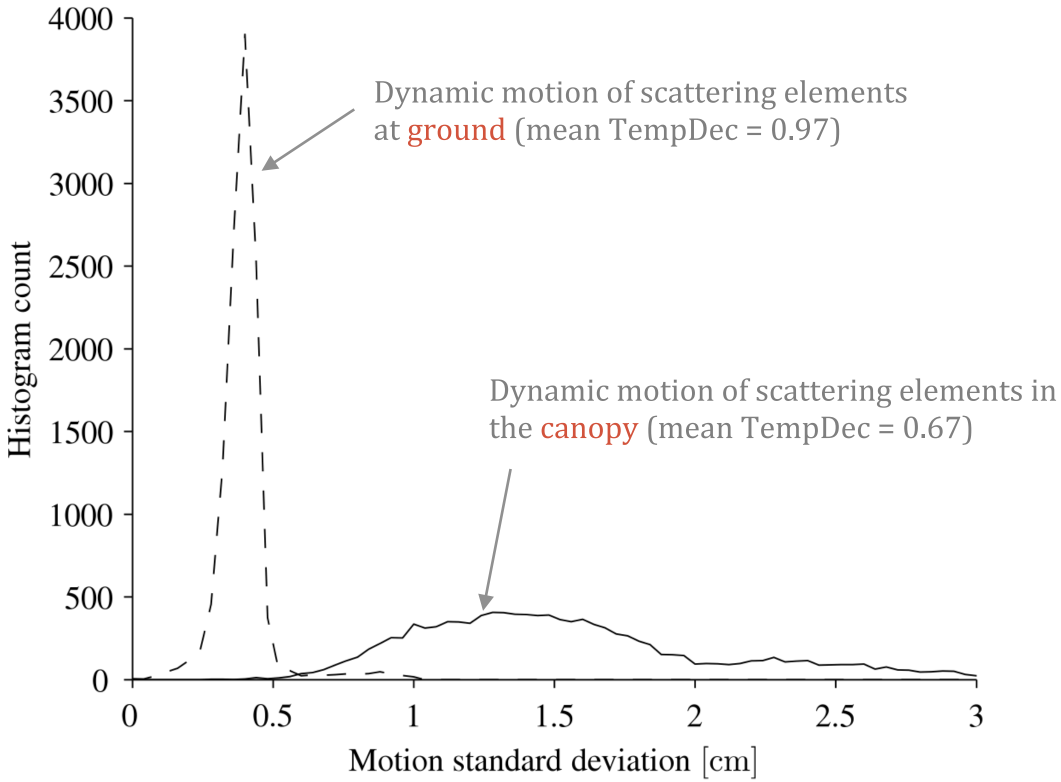
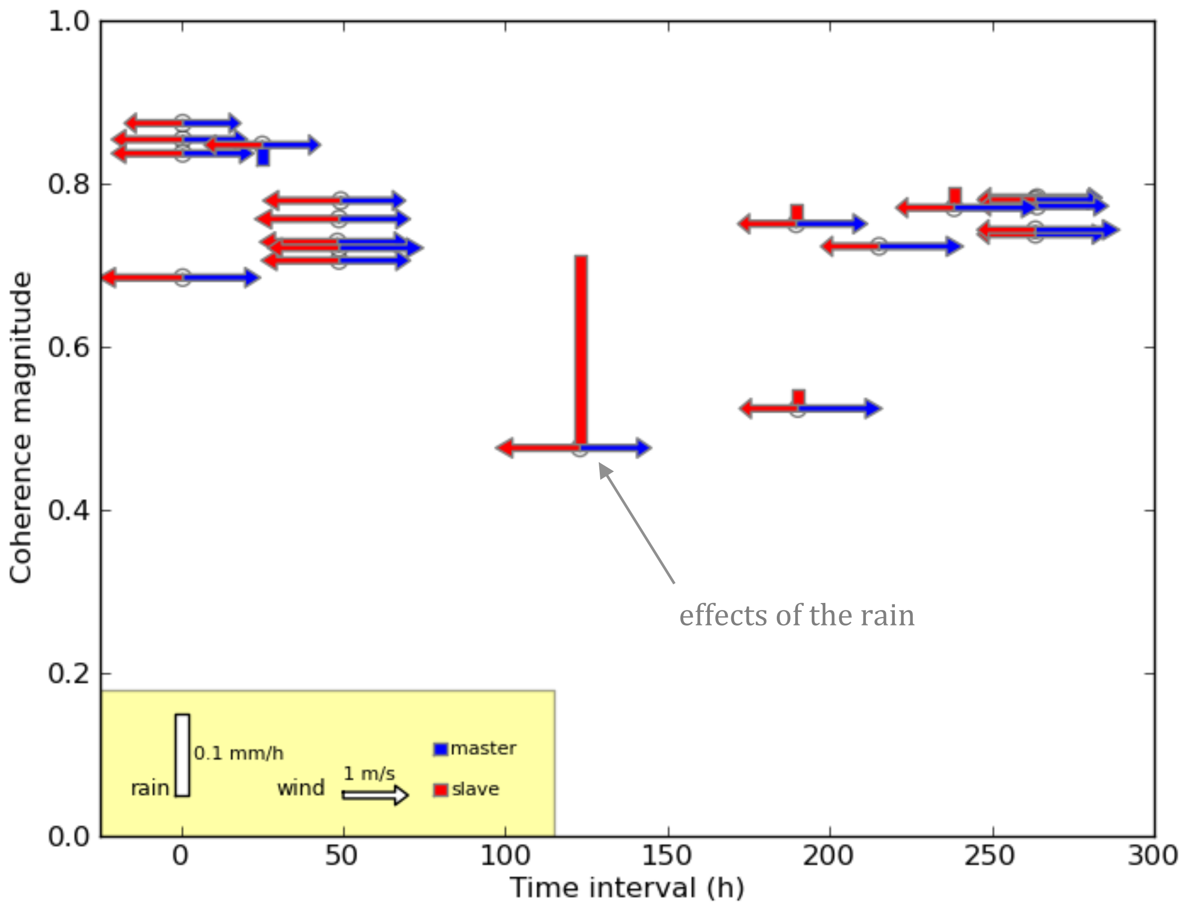


Comparison UAVSAR time series and weather data

Coherence, precipitation and wind data (Harvard Forest, MA)



Conclusions

- In repeat-pass Pol-InSAR scenario temporal decorrelation must be modeled in order to extract ecosystem structural parameters
- We have proposed a physical model of temporal decorrelation and a new method for extracting canopy height from single-baseline, repeat-pass Pol-InSAR data
- Model and method validated with numerical simulations and JPL/UAVSAR data
- Attractive avenue for estimating forest parameters using Pol-InSAR data from proposed radar missions (DESDynI, ALOS-2, BIOMASS, SENTINEL-1)