Tackling temporal decorrelation with the RMoG model

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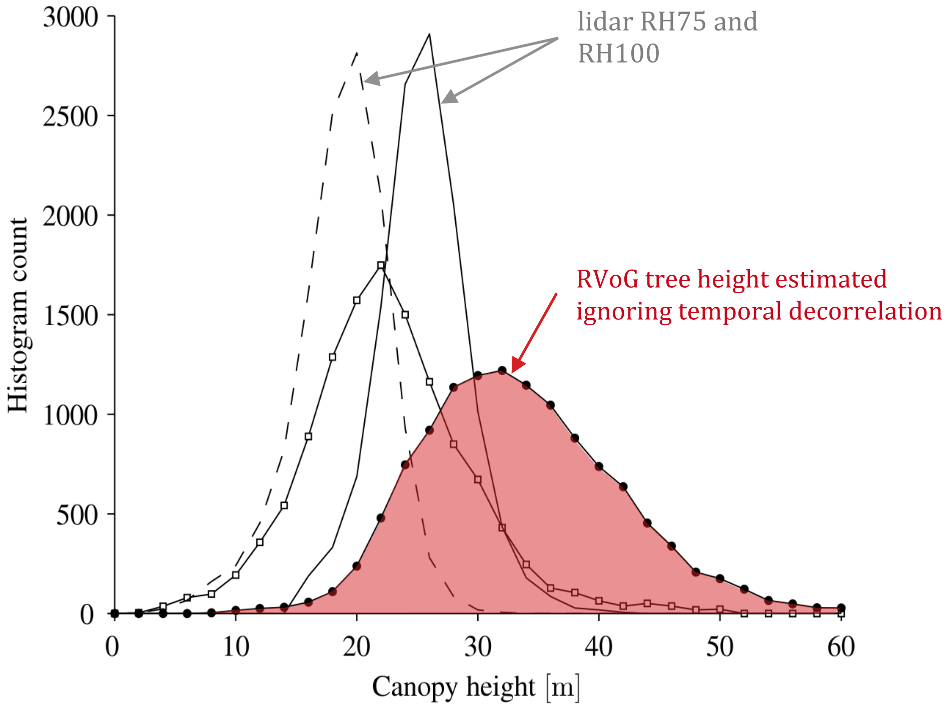
Outline

- 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

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)



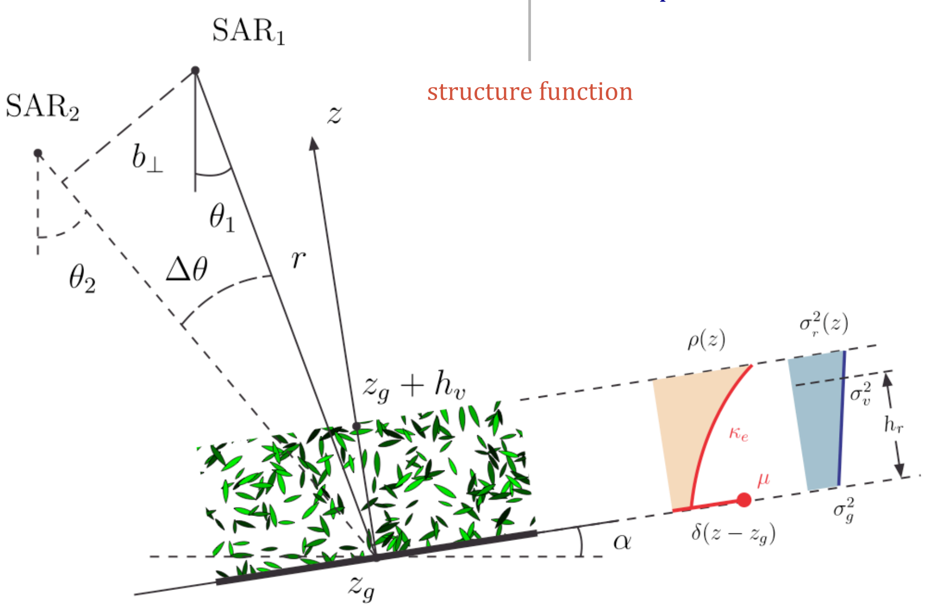
The RMoG model

- 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)

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

temporal function

structure function



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

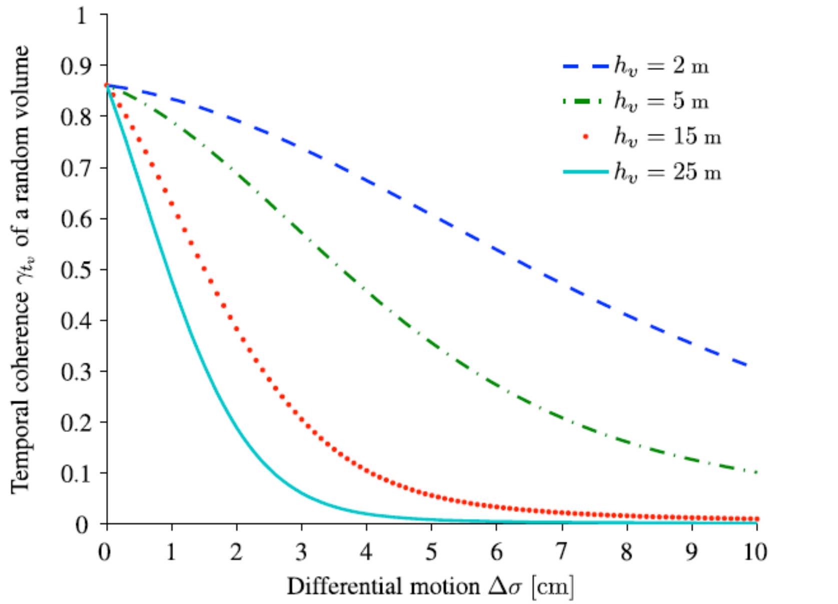
$$\gamma_{t_g} = \exp\left[-\frac{1}{2}\left(\frac{4\pi}{\lambda}\right)^2 \sigma_g^2\right]$$

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)

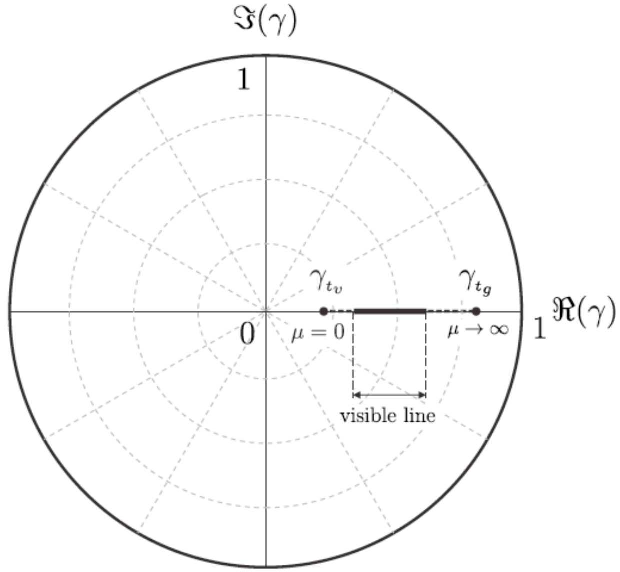


$$p_1 = \frac{2\kappa_e}{\cos(\theta - \alpha)}, \qquad p_2 = p_1 + jk_z, \qquad p_3 = -\frac{\Delta\sigma^2}{2h_r}\left(\frac{4\pi}{\lambda}\right)^2$$

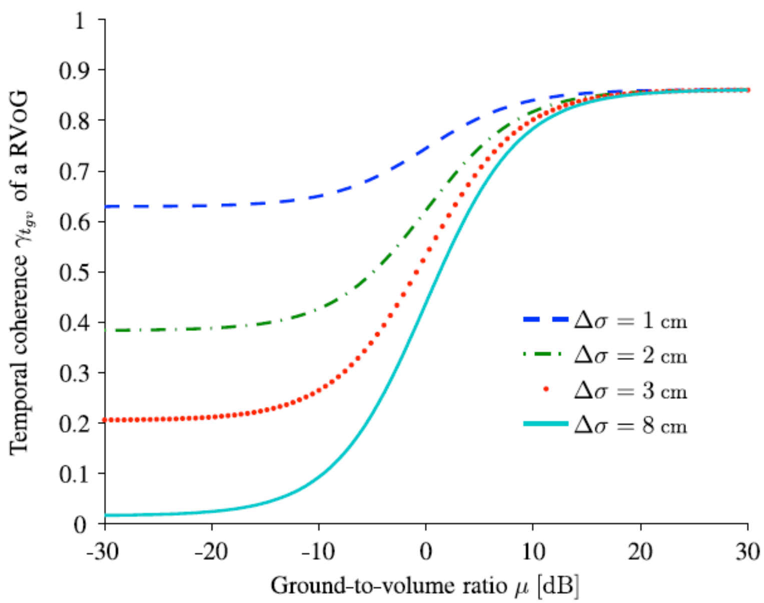
Key properties of the RMoG model

property n. 2

Coherence locus of RMoG temporal decorrelation



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.

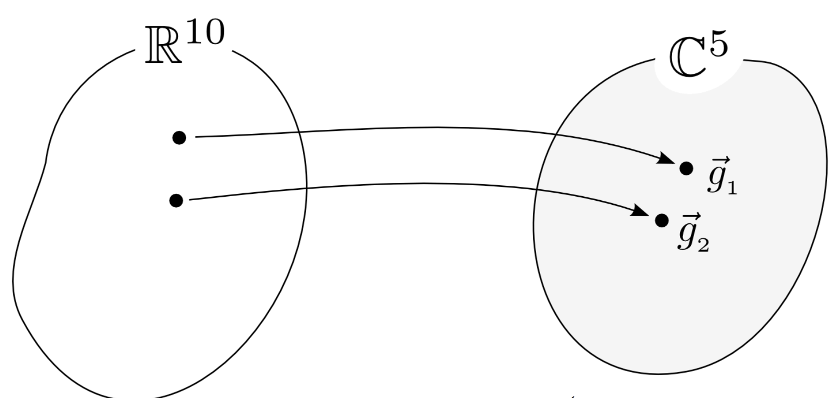
Part II
Inversion of the RMoG model

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

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

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

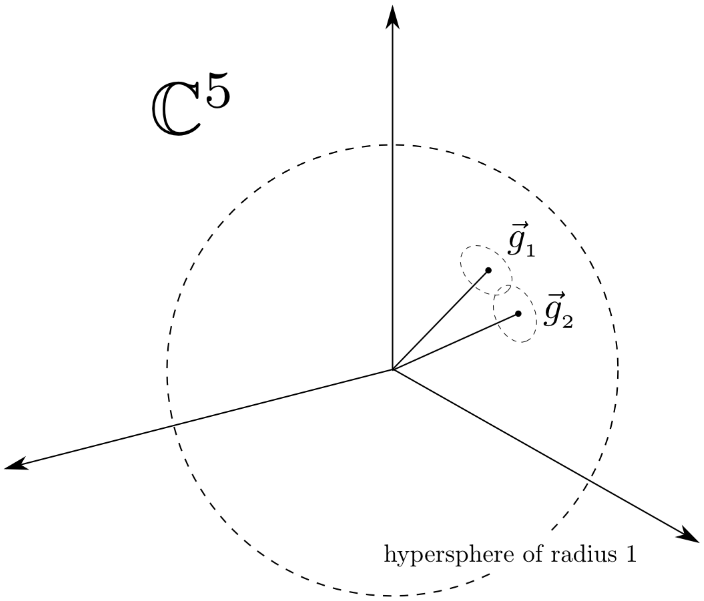


$$\vec{g} = (\gamma_1, \gamma_2, \gamma_3, \gamma_4, \gamma_5)^T$$

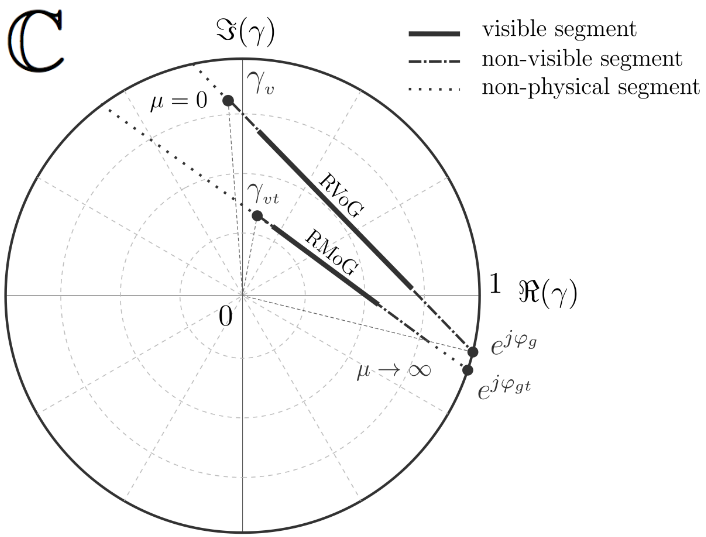
K. Papathanassiou and S. Cloude, "Single-Baseline Polarimetric SAR Interferometry," TGRS, vol. 39, no. 11, pp. 2352–2363, 2001.

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

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

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

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

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

$$\sigma_v \geq \sigma_g$$

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

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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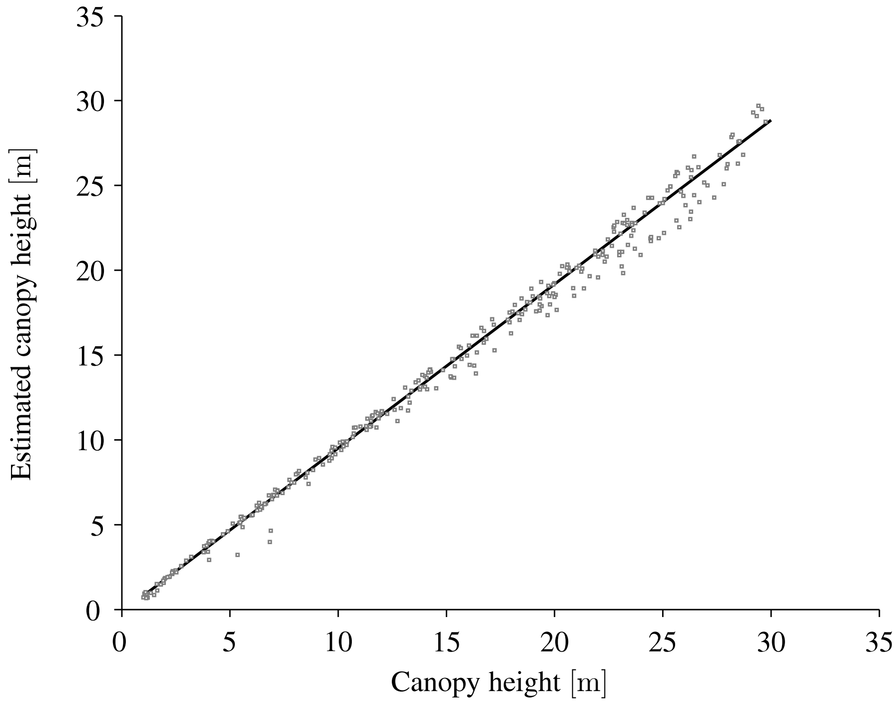

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  $h_v \in [0,\, 30]$ m

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

  $\sigma_g \in [0,\, 1]$ 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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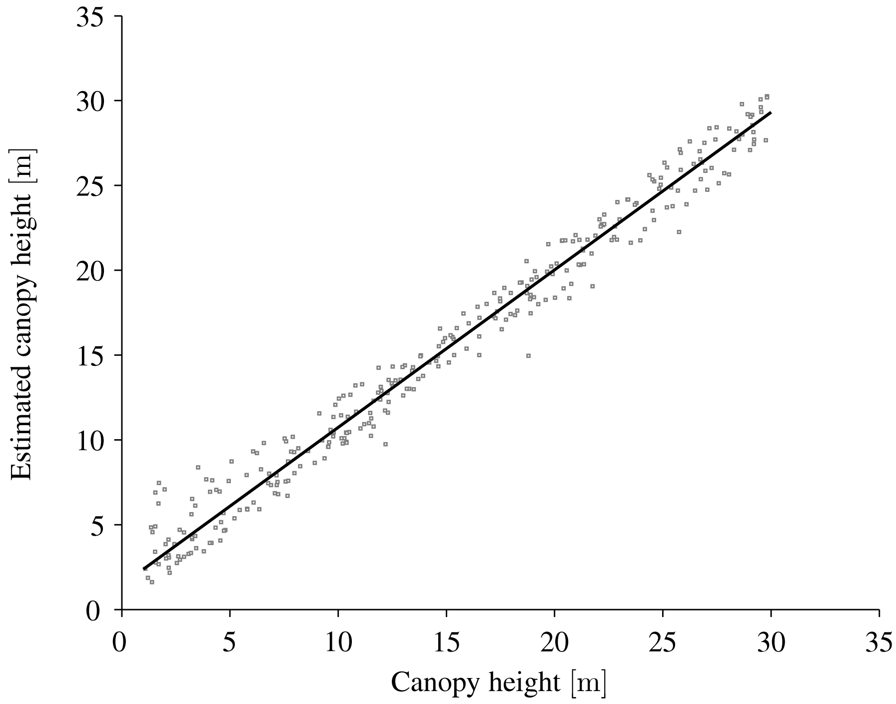


RMoG inversion: Conditioning of the solution

RMoG numerical simulations

- linear motion variance (RMoG model)

$$\sigma^2 = \sigma_g^2 + (\sigma_v^2 - \sigma_g^2)\frac{z - z_g}{h_r}$$

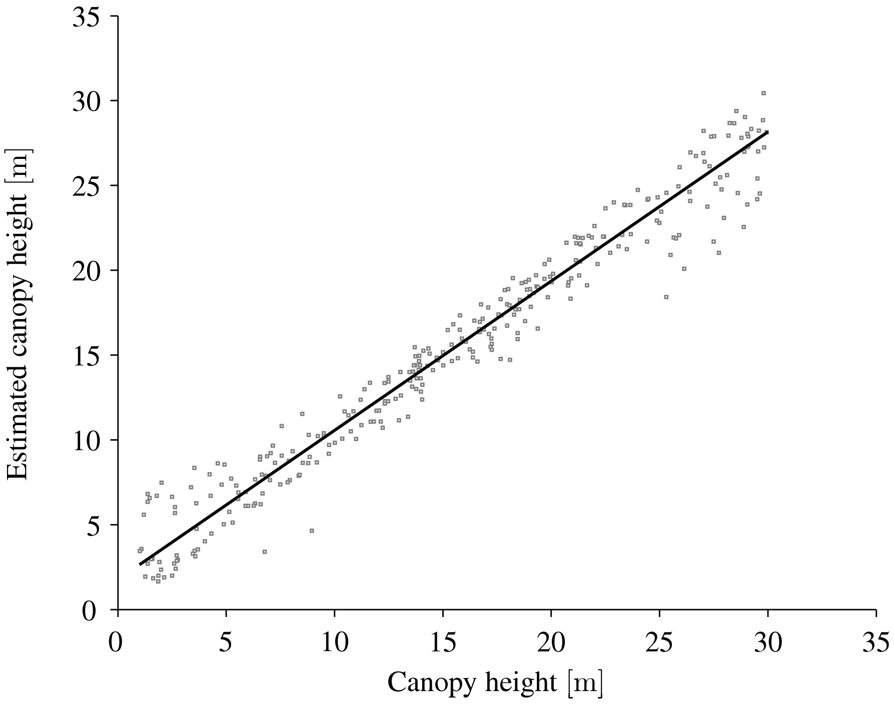
- exponential motion variance

$$\sigma^2 = \sigma_g^2 \exp\left[\frac{z - z_g}{h_r} \ln \frac{\sigma_v^2}{\sigma_g^2}\right]$$

- quadratic motion variance

$$\sigma^2 = \sigma_g^2 + (\sigma_v^2 - \sigma_g^2)\sqrt{\frac{z - z_g}{h_r}}$$

- Exponential- and quadratic-based coherences inverted using the RMoG model

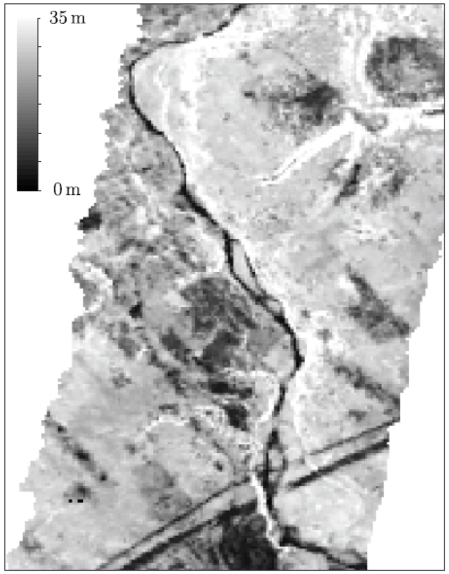


RMoG model VS reality: UAVSAR experiments

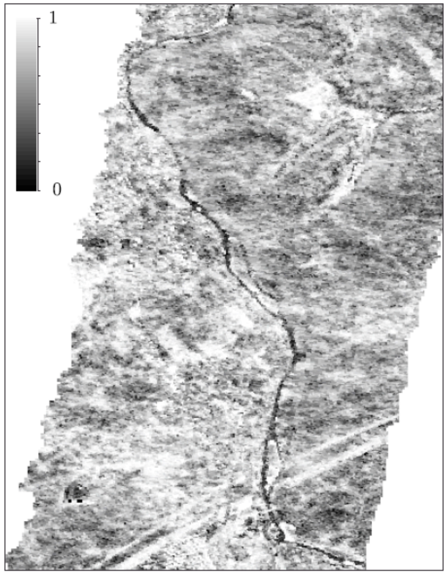
Validation of temporal decorrelation model ($b_\perp = 0$)

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

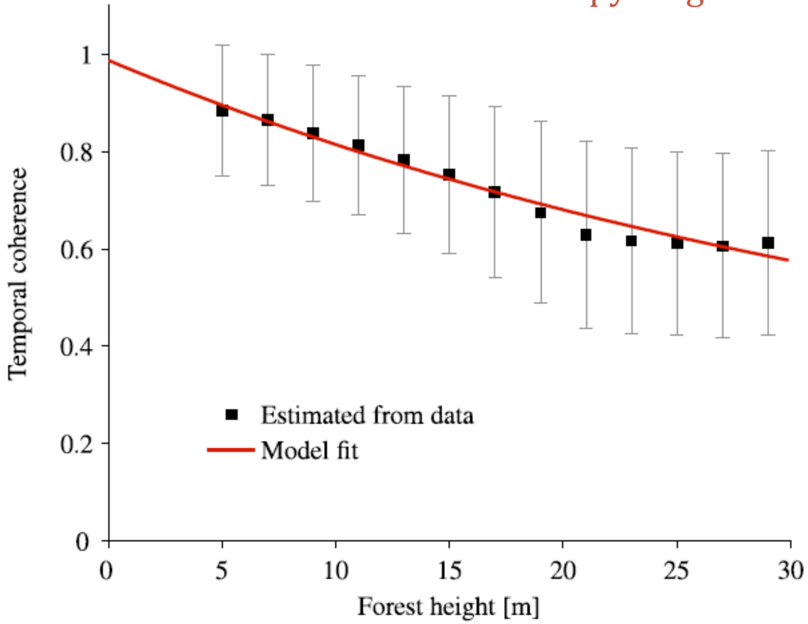
LVIS lidar canopy height



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



validation of dependence of temporal decorrelation on canopy height



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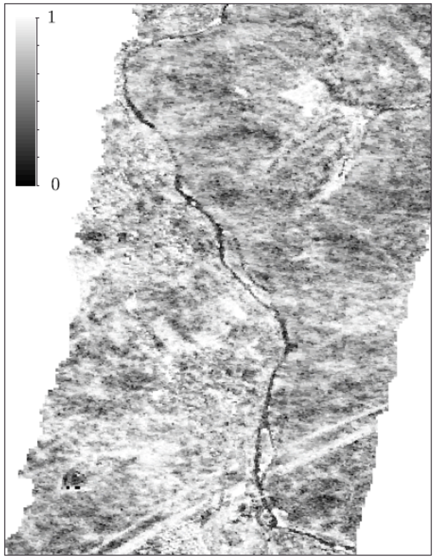
Validation of temporal decorrelation model ($b_{\perp} = 0$)

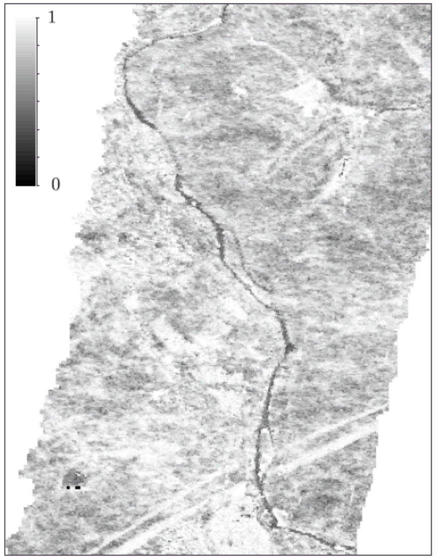
Quebec (Canada); 45 min temporal interval; ~zero vertical wavenumber; L-band UAVSAR

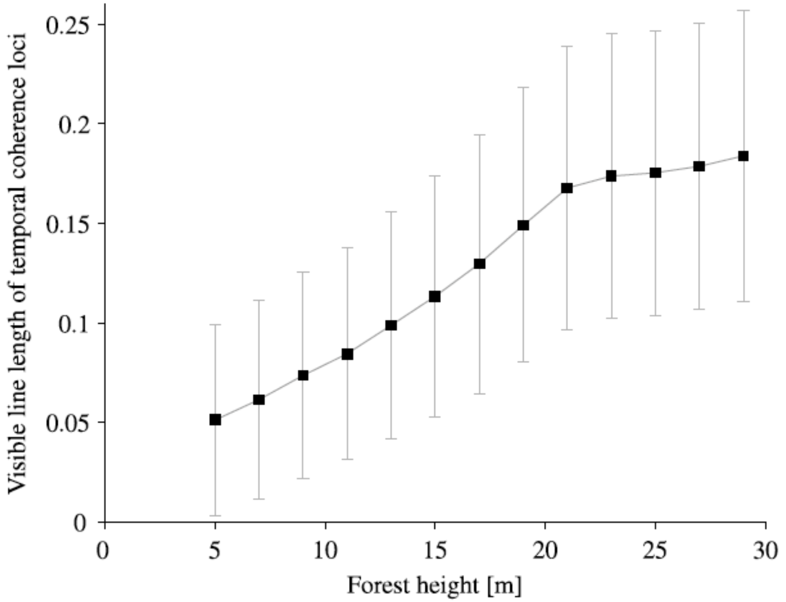
validation of dependence of temporal correlation on wave polarization

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



optimized high coherence





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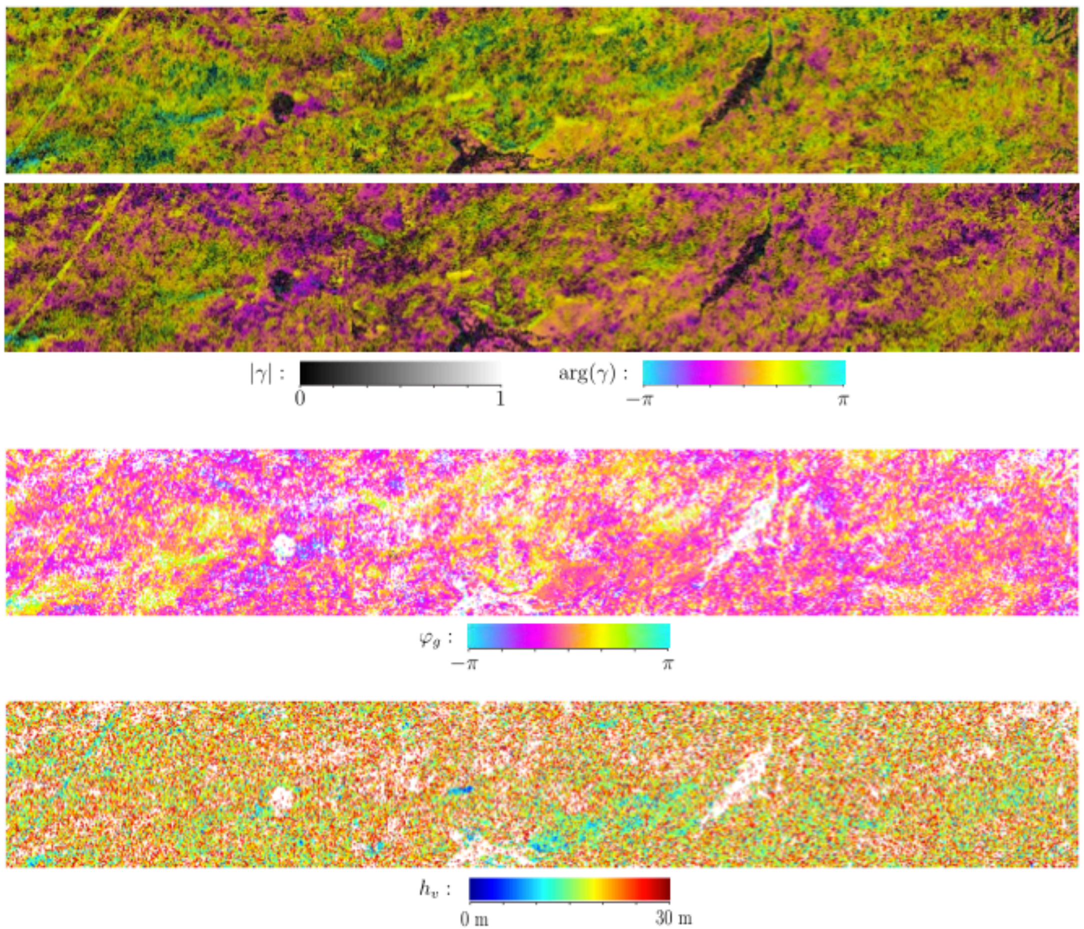
Tree height from Pol-InSAR UAVSAR data

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



Canopy-dominated coherence

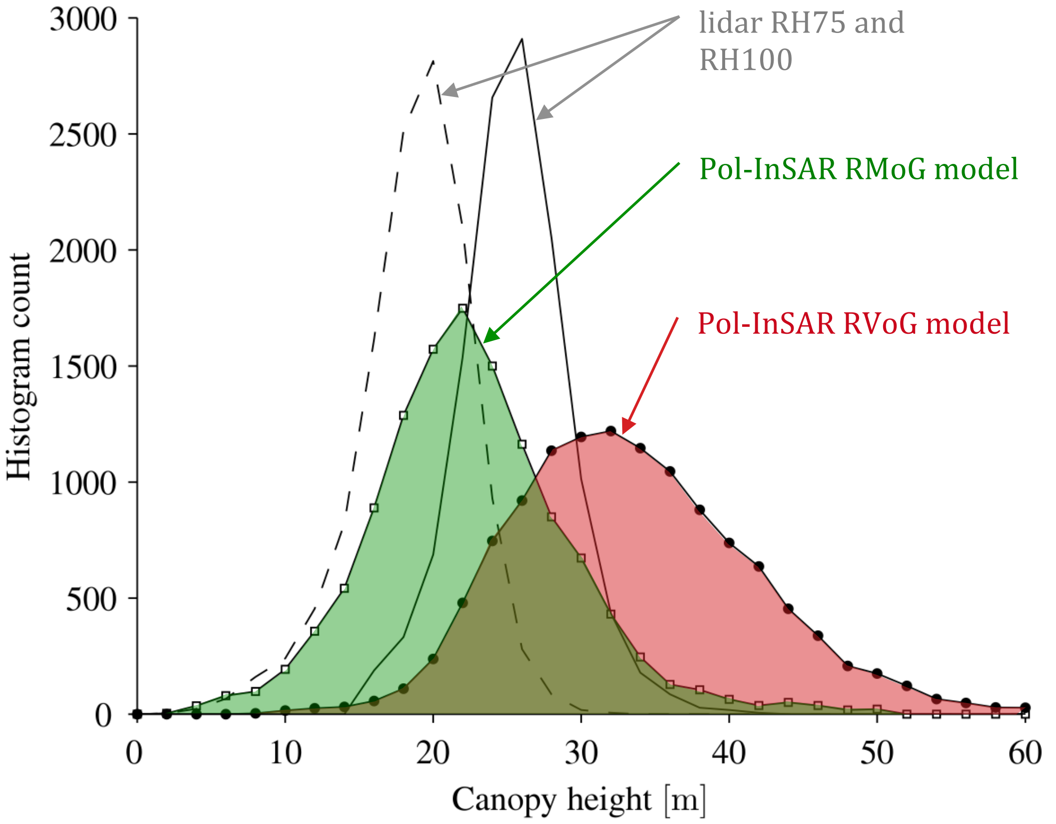
Ground-dominated coherence

Estimated ground topography

Estimated canopy height

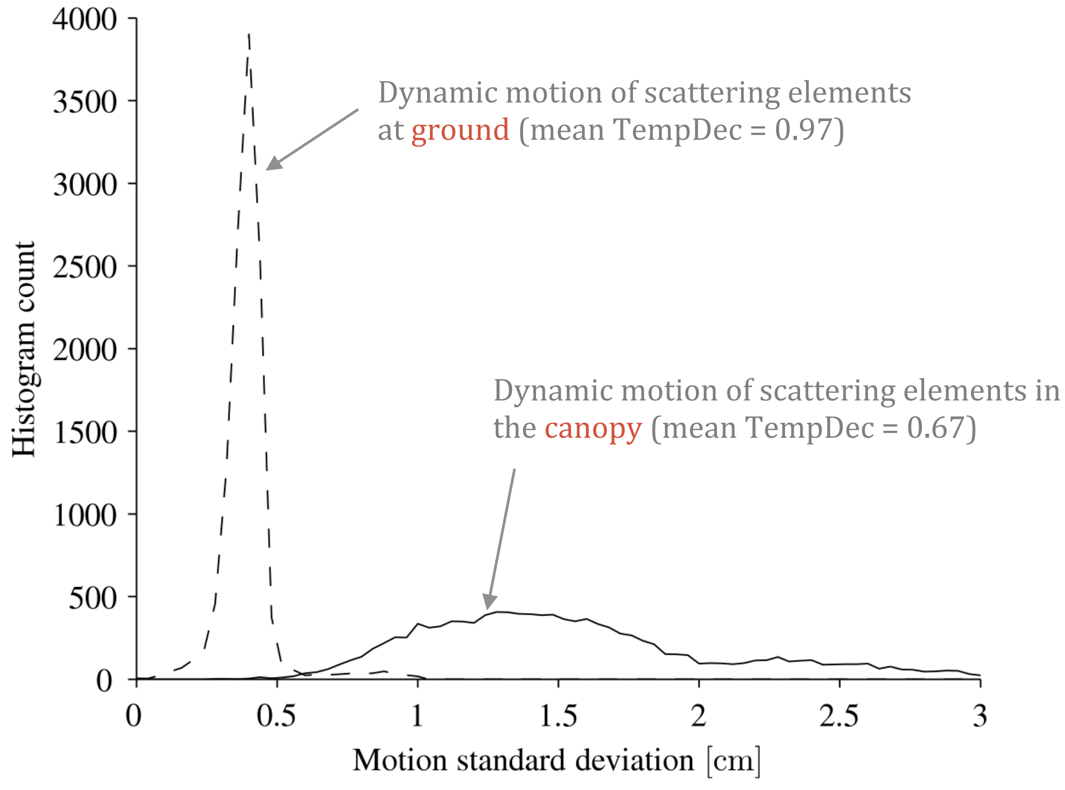
Tree height from Pol-InSAR UAVSAR data VS lidar LVIS

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



RMoG temporal parameters from Pol-InSAR UAVSAR data

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



Conclusions

- Proposed an inversion strategy for estimating tree height from single-baseline, repeat-pass Pol-InSAR data using the RMoG model
    - Current strengths: tree height from single-baseline RP-PolInSAR; model-based inversion with no a-priori assumptions; available with open-source libraries
    - Current weaknesses: length of visible line might be short; RMoG doesn't model complex temporal phenomena; inversion might be time consuming
- Model and method validated with numerical simulations and JPL/UAVSAR data
- Attractive avenue for estimating forest parameters using Pol-InSAR data from forthcoming radar missions (ALOS-2, SENTINEL-1, DESDynI, BIOMASS)