Extracting vegetation 3D structure from repeat-pass Pol-InSAR data: The RMoG model

Marco Lavalle, Scott Hensley and Ralph Dubayah

Jet Propulsion Laboratory, California Institute of Technology

Background and motivation

- Oct 2011 NASA CCE workshop (Alexandria, VA)
  - cancellation of DESDynI lidar motivated Pol-InSAR side meeting
  - lack of US experience with Pol-InSAR (peer-reviewed papers and data)
  - great worry of temporal decorrelation

- Radar missions with Pol-InSAR capabilities
  - JAXA/ALOS-2 (L-band)
  - ESA/BIOMASS (P-band)
  - ESA/SENTINEL-1 (C-band)
  - DLR/TERRASAR-X (X-band)

Objectives and outline

- Objectives
  - to design a method for extracting canopy height and structure from radar data
  - using single-baseline interferometry and
  - robust against temporal decorrelation

- Outline of the talk
  - what is Pol-InSAR
  - new physical model of temporal decorrelation
  - RMoG model
  - canopy height estimation with JPL/UAVSAR data
  - conclusions

What is Pol-InSAR?

- Radar technique
  - proposed 15 years ago (Treuhaft, 1996; Cloude, 1998)

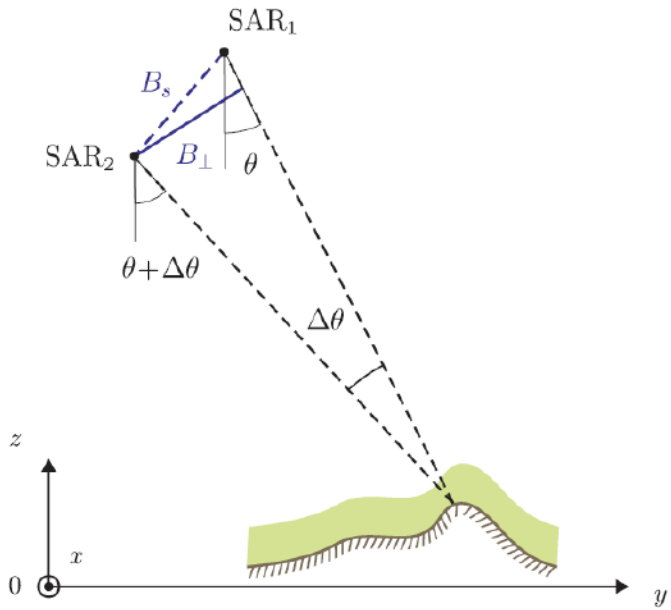
Pol In SAR

polarimetry

interferometry

- Basic idea
  - polarimetry "sees" different scattering mechanisms
  - interferometry associates the 3D location to a scattering mechanism
  - coherent combinations of polarization give continuous set of complex correlations

- Applications
  - canopy height estimation
  - vegetation parameters, vertical structure, biomass estimation



Canopy height from Pol-InSAR… does it work?

- Peer-reviewed publications

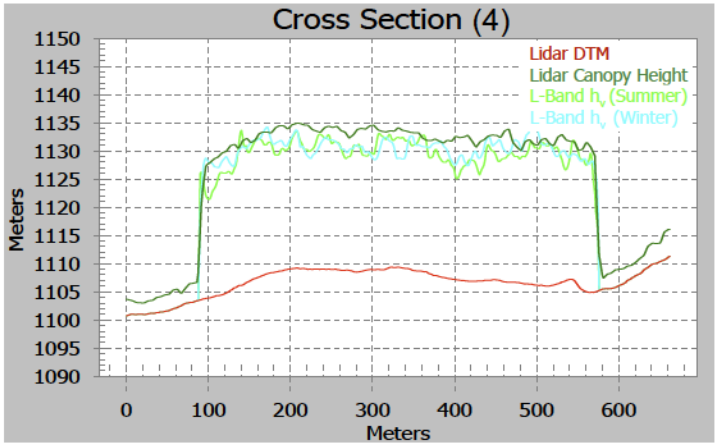
1996

- Treuhaft, 1996
- Cloude, 1997; Cloude 1998
- Treuhaft, 2000
- Papathanassiou, 2001
- Tabb, 2002
- Cloude, 2003
- Mette, 2004
- Colin, 2005
- Ballester-Berman, 2005
- Papathanassiou, 2005
- Cloude, 2006
- Ballester-Berman, 2007
- Lopez-Sanchez, 2007
- Neumann, 2008
- Ferro-Famil, 2008
- Garestier, 2009
- Haijnsek, 2009
- Lavalle, 2010
- Garestier, 2010
- Lopez-Martinez, 2010
- Tebaldini, 2010

2011

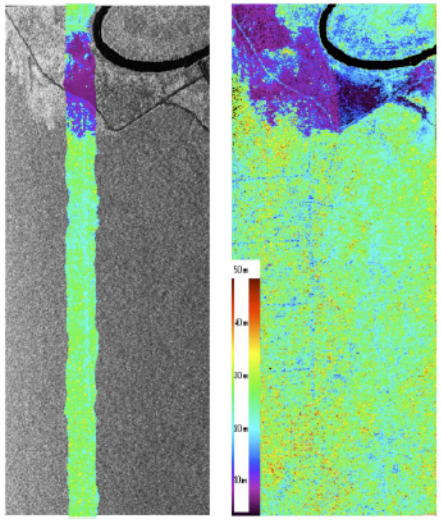
- Lavalle, 2011

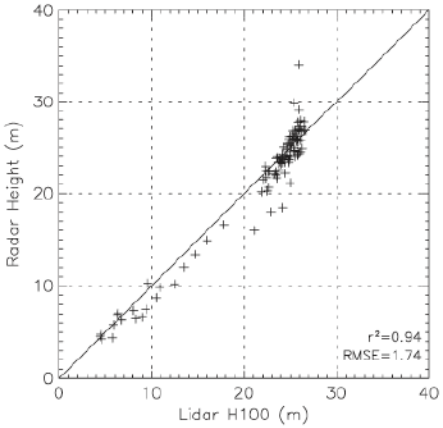
INTERMAP Tech., presented at PolInSAR workshop, Jan. 2011



Lidar height

Radar height



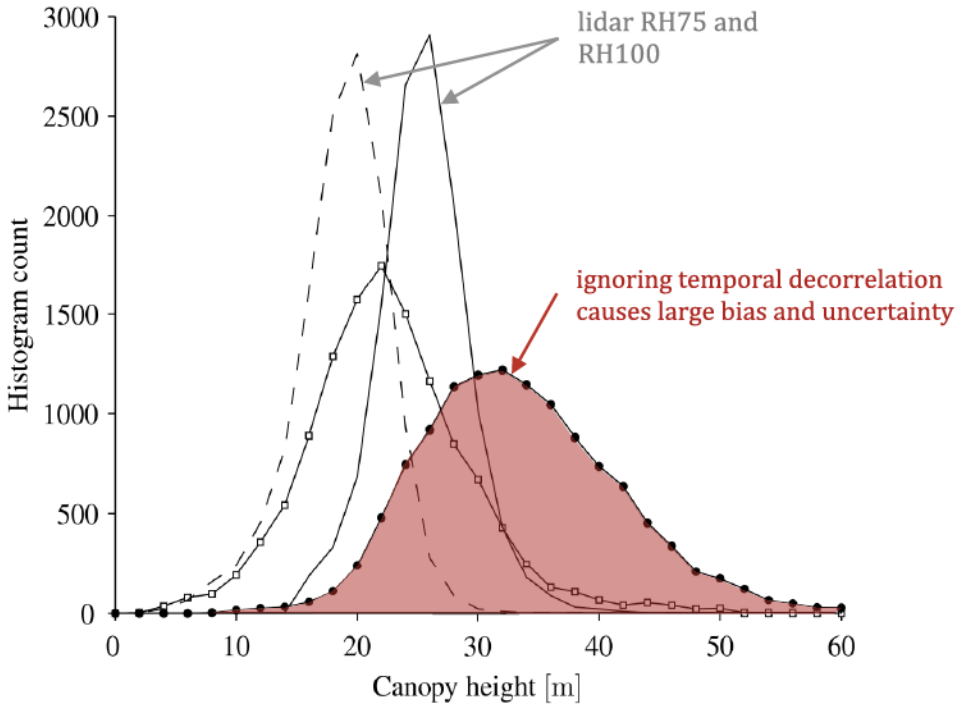


Hajnsek, I. et al., IEEE TGRS, 2009.

Pol-InSAR and temporal decorrelation… the problem

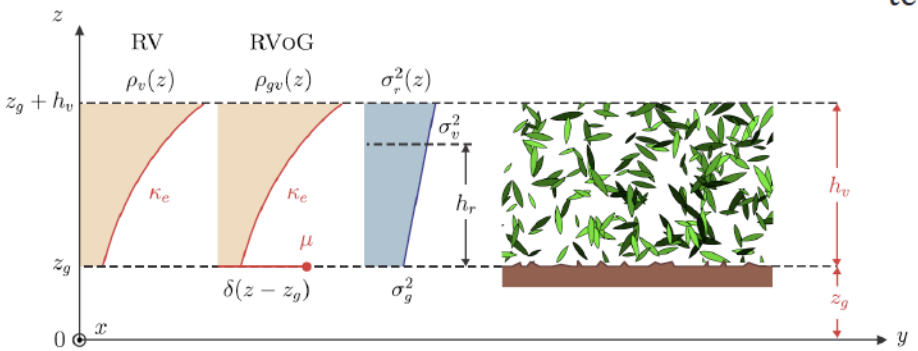
- Measured interferometric correlation is affected by two main factors: volumetric and temporal decorrelation
- In previous approaches (RVoG model), canopy height and structure are extracted from measures of volumetric decorrelation
- Temporal decorrelation, if ignored or not properly compensated, causes large errors

Canopy height estimated from JPL/UAVSAR data over Harvard Forest, MA



Temporal decorrelation model

Temporal decorrelation model



temporal coherence

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

structure function

$$\rho_{gv}(z) = \rho_v(z) + \varrho_g \exp\left(-\frac{2\kappa_e}{\cos\theta} h_v\right) \delta(z - z_g)$$

$$\rho_v(z) = \varrho_v \exp\left[\frac{2\kappa_e}{\cos\theta}(z - z_g - h_v)\right]$$

temporal function

$$\begin{aligned} \sigma_r^2(z) &= \sigma_g^2 + (\sigma_v^2 - \sigma_g^2)\, \frac{z - z_g}{h_r} \\ &= \sigma_g^2 + \Delta\sigma^2 \frac{z - z_g}{h_r} \end{aligned}$$

$$\Delta\sigma^2 = \sigma_v^2 - \sigma_g^2\,,$$

M. Lavalle, M. Simard and S. Hensley, "A temporal decorrelation model for polarimetric radar interferometers", IEEE TGRS 2011.

Temporal decorrelation model

- physical model (no empirical parameters)
- closed-form expression

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

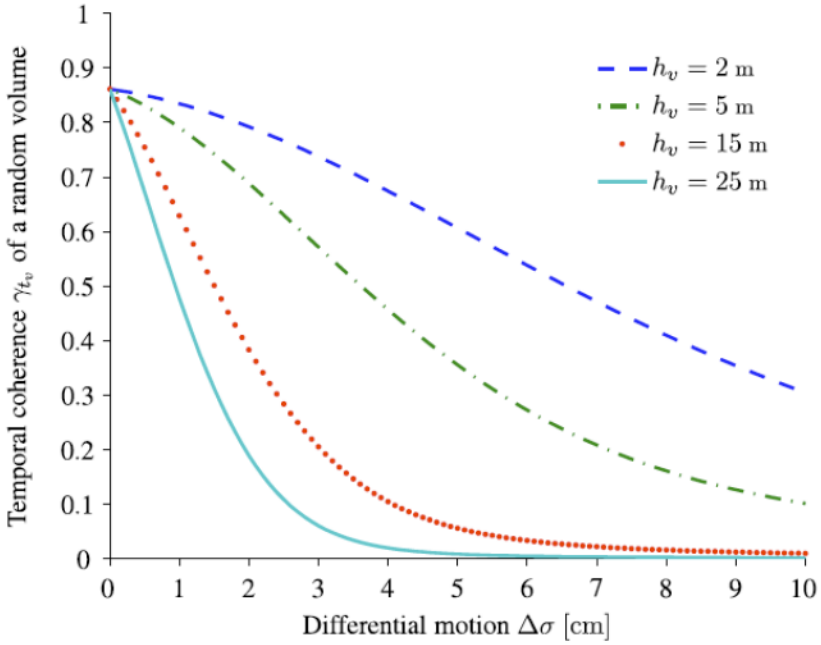
$$\gamma_{t_g} - \exp\left[-\frac{1}{2} \left(\frac{4\pi}{\lambda} \right)^2 \sigma_g^2 \right]$$

$$\gamma_{t_{gv}} = \frac{\mu \gamma_{t_g} + \gamma_{t_v}}{\mu + 1}$$

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

new property n. 1

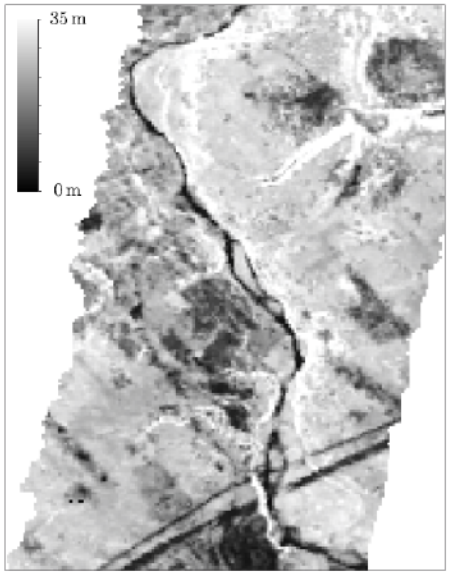
temporal decorrelation depends on vegetation structure (e.g. canopy height)



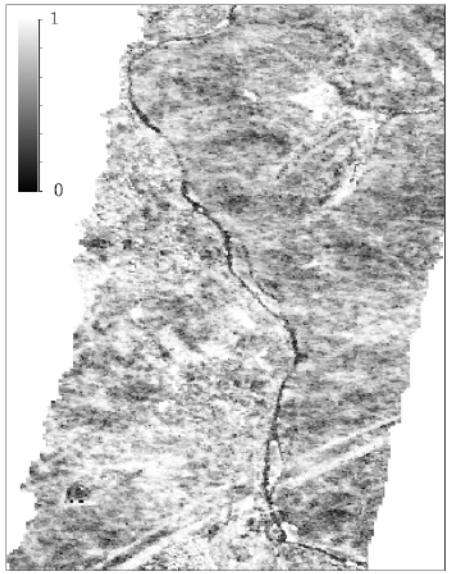
M. Lavalle, M. Simard and S. Hensley, "A temporal decorrelation model for polarimetric radar interferometers", IEEE TGRS 2011.

Validation of temporal decorrelation model

lidar canopy height (LVIS)

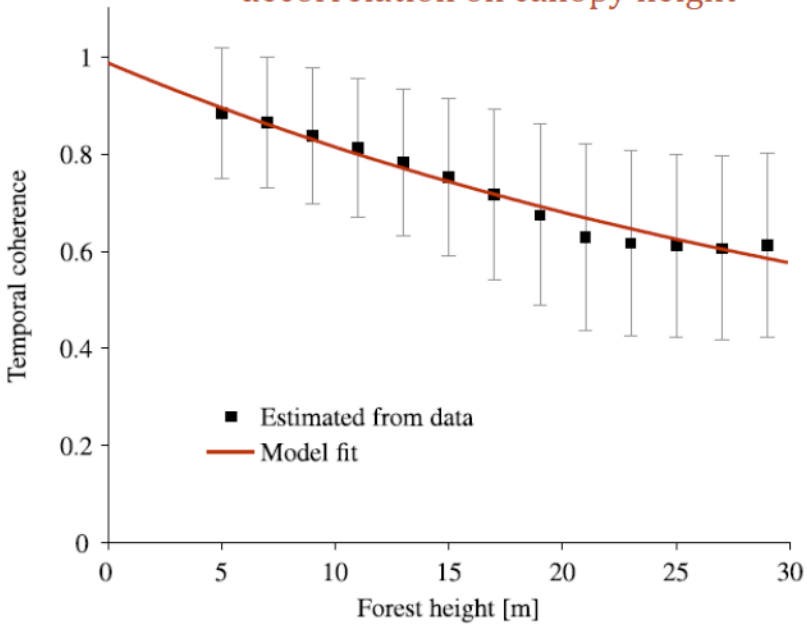


radar coherence (UAVSAR)



JPL/UAVSAR L-band airborne radar
HV temporal coherence map
zero spatial baseline
45 min temporal baseline
Laurentides, Quebec

validation of dependence of temporal decorrelation on canopy height



M. Lavalle, M. Simard and S. Hensley, "A temporal decorrelation model for polarimetric radar interferometers", IEEE TGRS 2011.

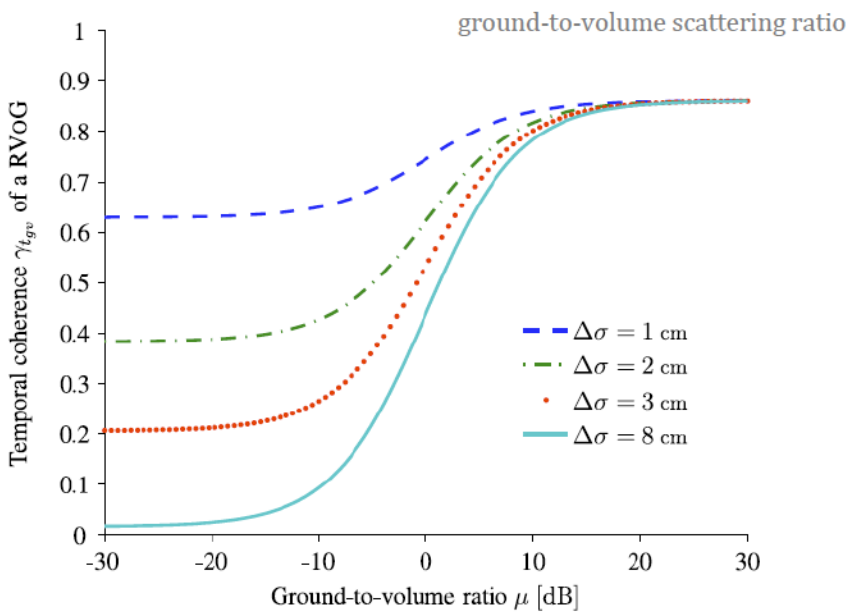
Temporal decorrelation model

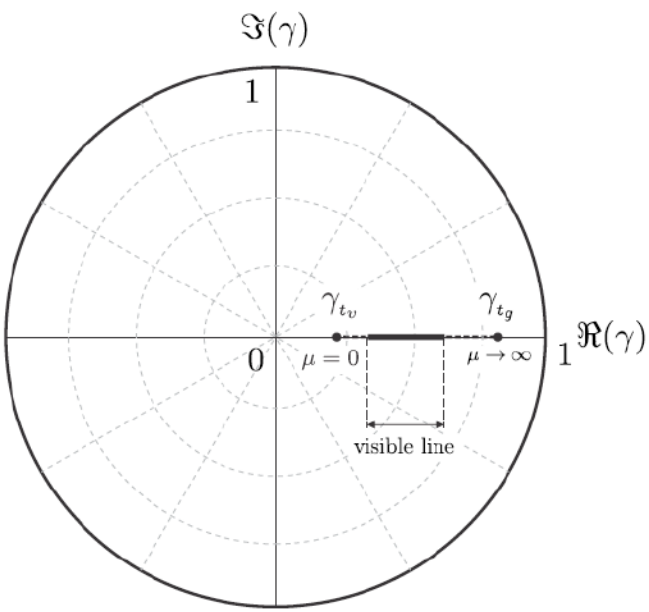
$$\gamma_{t_{gv}} = \frac{\mu\,\gamma_{t_g} + \gamma_{t_v}}{\mu + 1}$$

ground-to-volume scattering ratio

new property n. 2

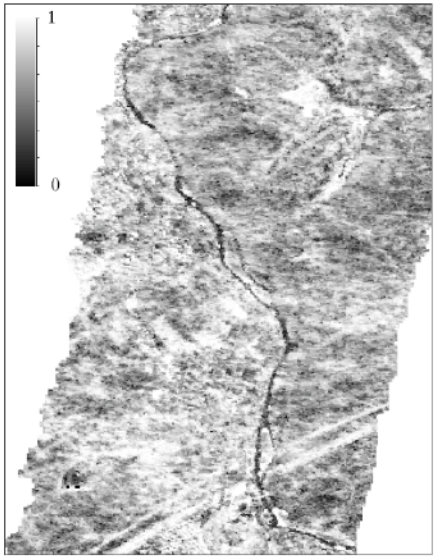
temporal decorrelation is sensitive to wave polarization



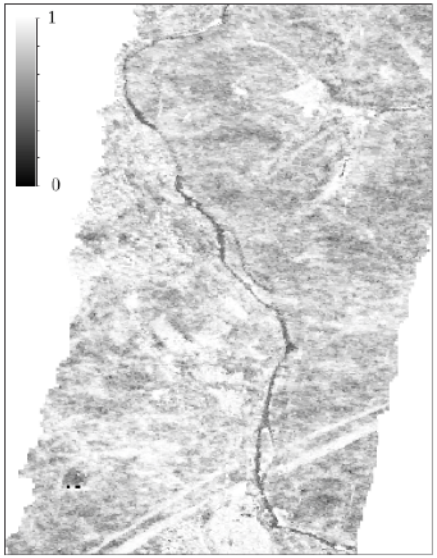


Validation of temporal decorrelation model

HV coherence



optimized high coherence



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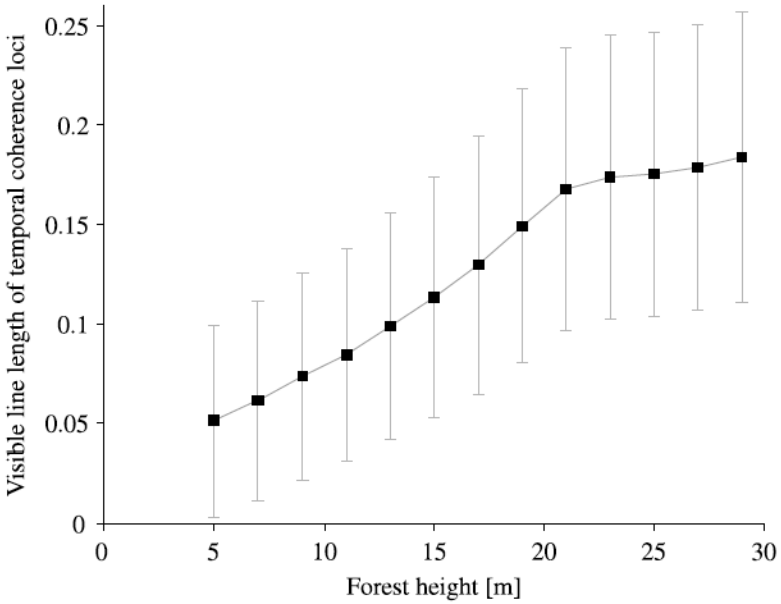

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Canopy height estimation

Temporal-volume decorrelation model

- Closed-form temporal-volume coherence model
- New model: RMoG (random motion over ground) model
- 4 structural + 2 temporal = 6 model parameters

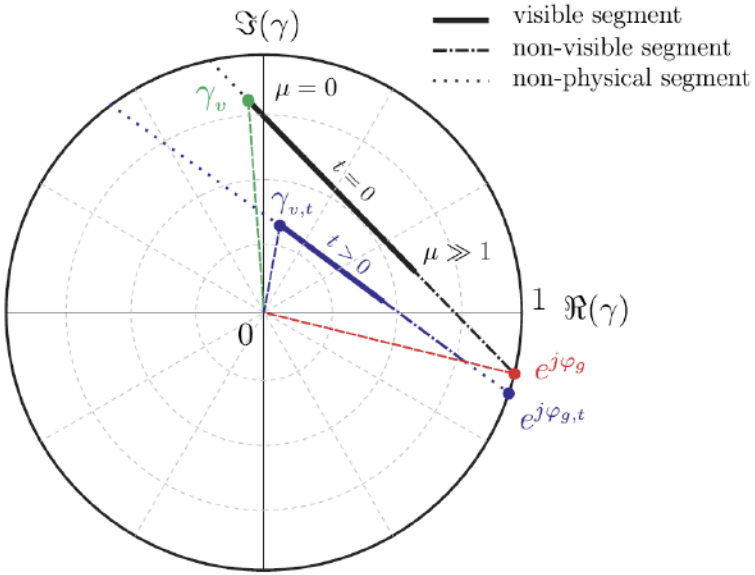
$$\gamma_{vt} = e^{j\varphi_g}\,\gamma_{t_g}\,\frac{p_1\left[e^{(p_2+p_3)h_v}-1\right]}{(p_2+p_3)\left(e^{p_1 h_v}-1\right)}$$

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

$$\boxed{\gamma = e^{j\varphi_g}\,\frac{\mu\,\gamma_{t_g}+\gamma_{vt}\,e^{-j\varphi_g}}{\mu+1}}$$

$$\gamma \neq \gamma_t\,\gamma_v$$

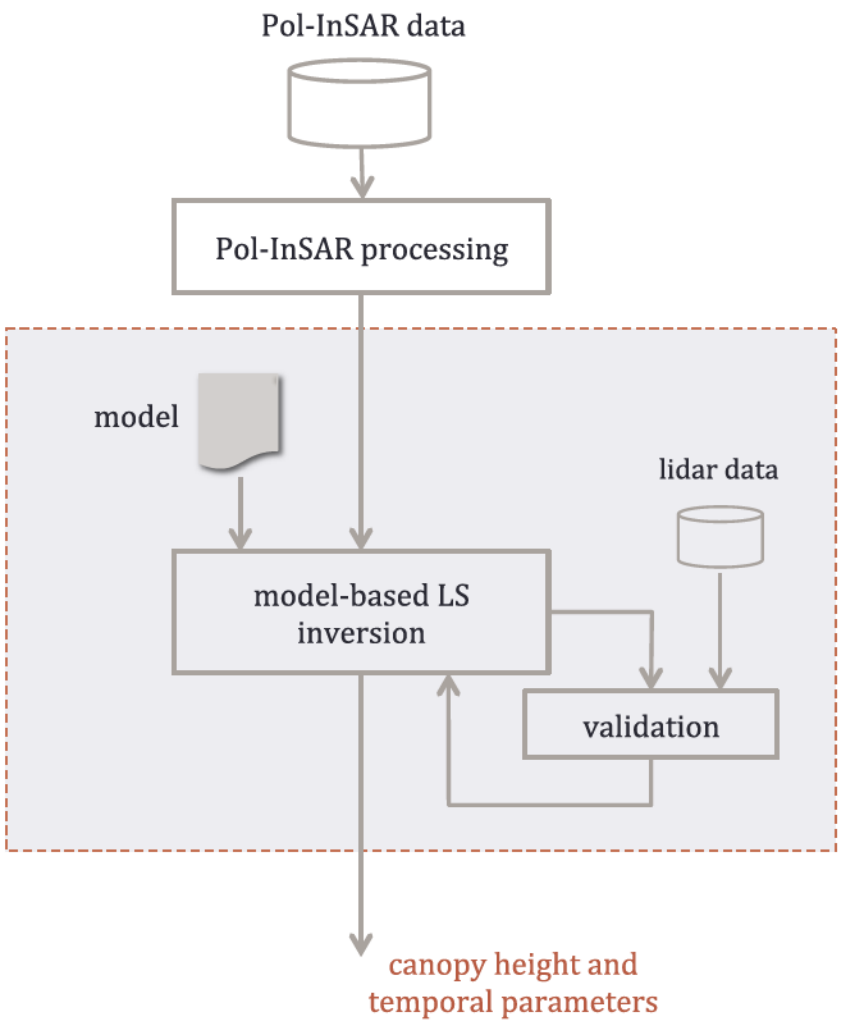
$$p_1 = \frac{2\kappa_e}{\cos(\theta-\alpha)}, \qquad p_2 = p_1 + jk_z, \qquad p_3 = -\frac{\Delta\sigma^2}{2h_r}\left(\frac{4\pi}{\lambda}\right)^2$$



M. Lavalle and S. Hensley, "Repeat-pass polarimetric SAR interferometry", IEEE TGRS 2011 (in review).

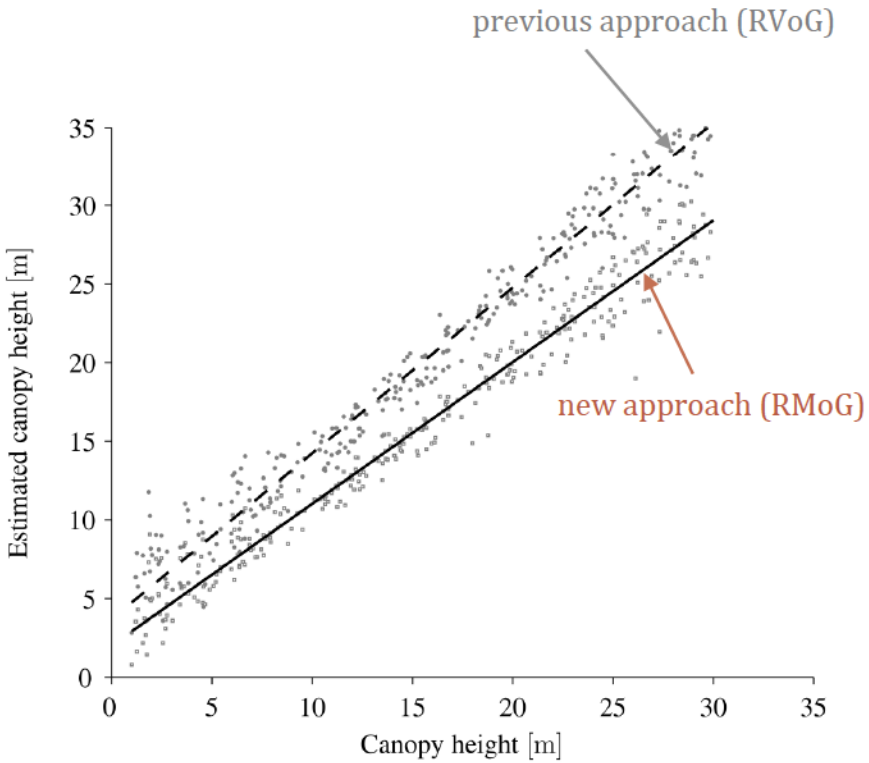
Method for canopy height estimation

- Single-baseline, repeat-pass data are processed to generated coherency matrix
- Coherence optimization algorithm calculates coherences close to top-canopy and ground
- Model-based LS inversion procedure estimates canopy height and temporal parameters



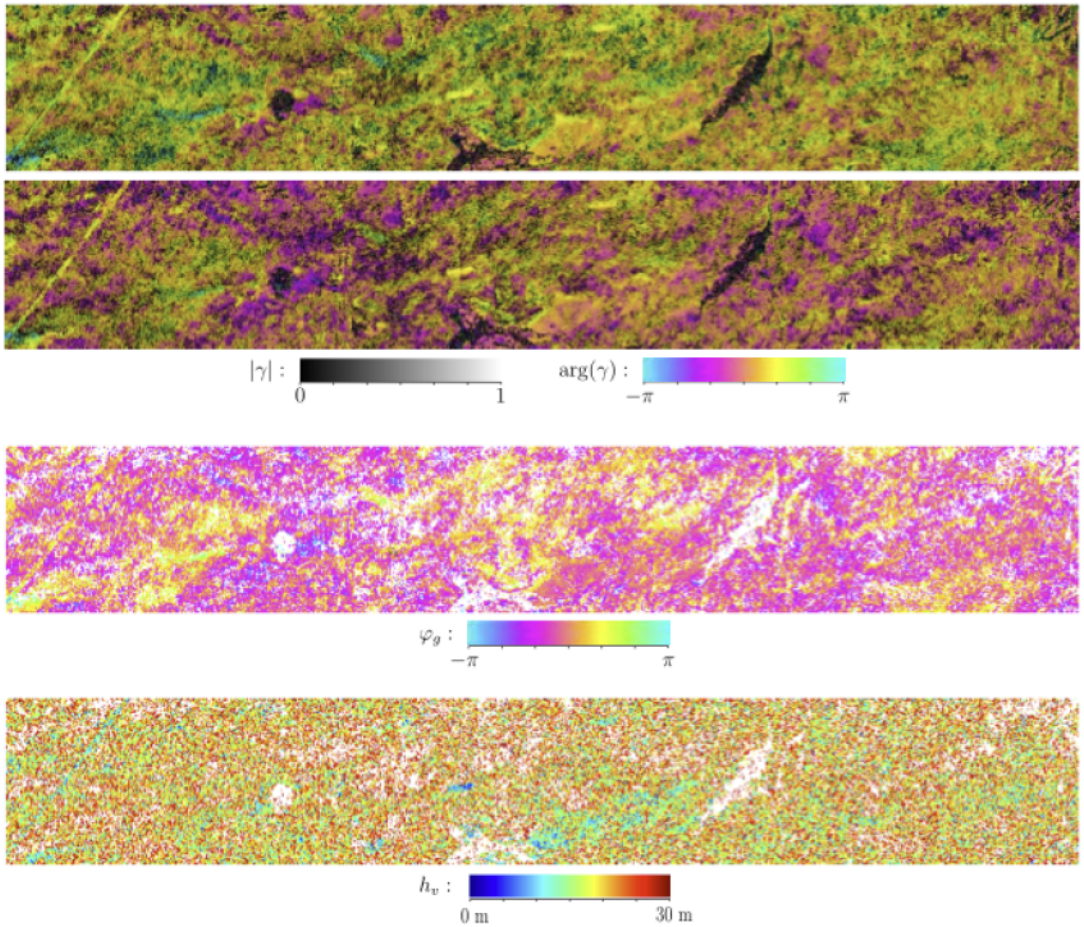
Error and uncertainty

- Numerical simulations
  - UAVSAR radar parameters
  - large range of values for forest parameters and temporal parameters
  - random noise added simulated data
- Canopy height error
  - RVoG model: RMSE 70% of total height
  - RMoG model: RMSE 20% of total height



Canopy height from Pol-InSAR UAVSAR data

Harvard Forest, MA



Canopy-dominated coherence

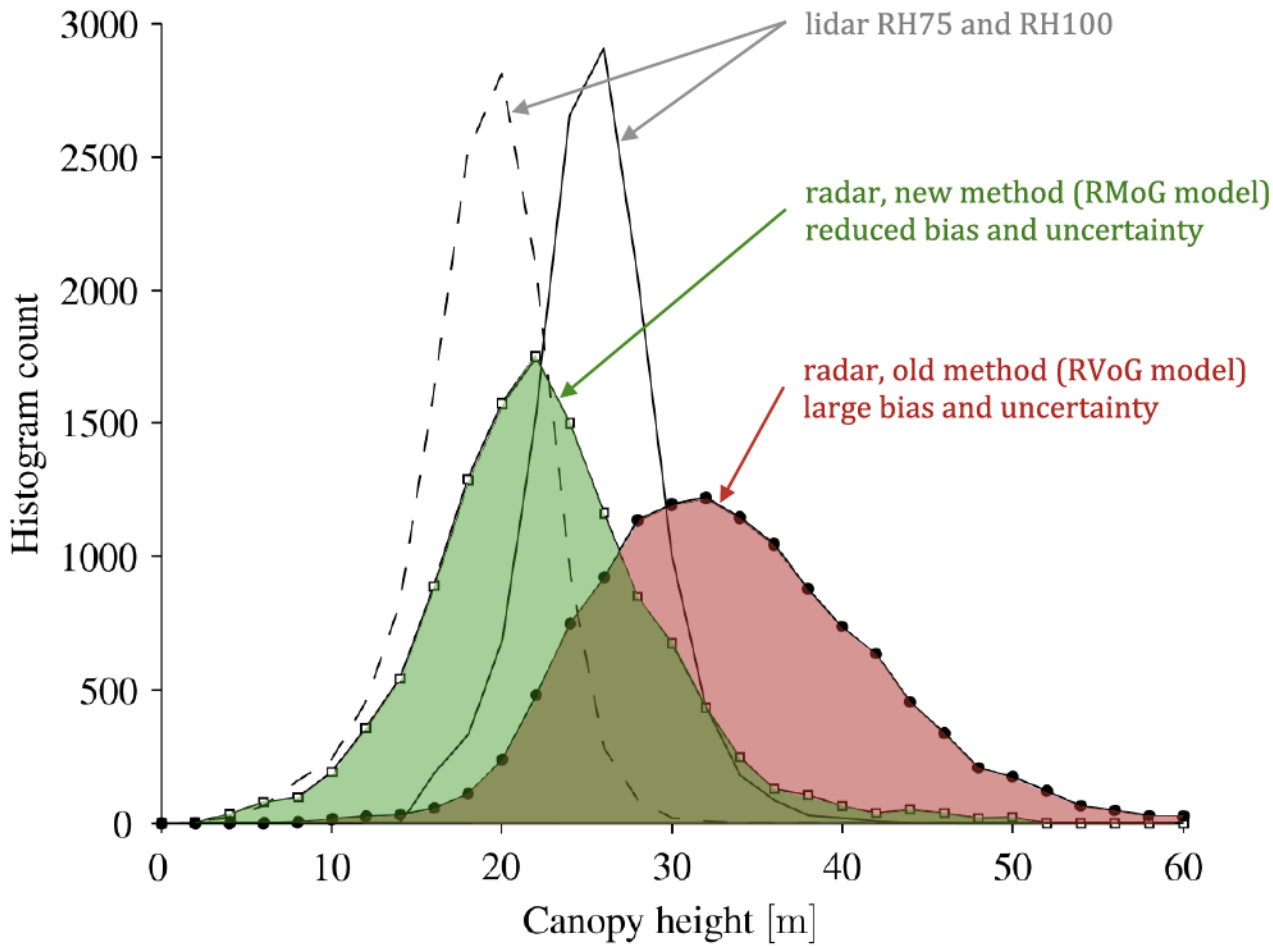
Ground-dominated coherence

Estimated ground topography

Estimated canopy height

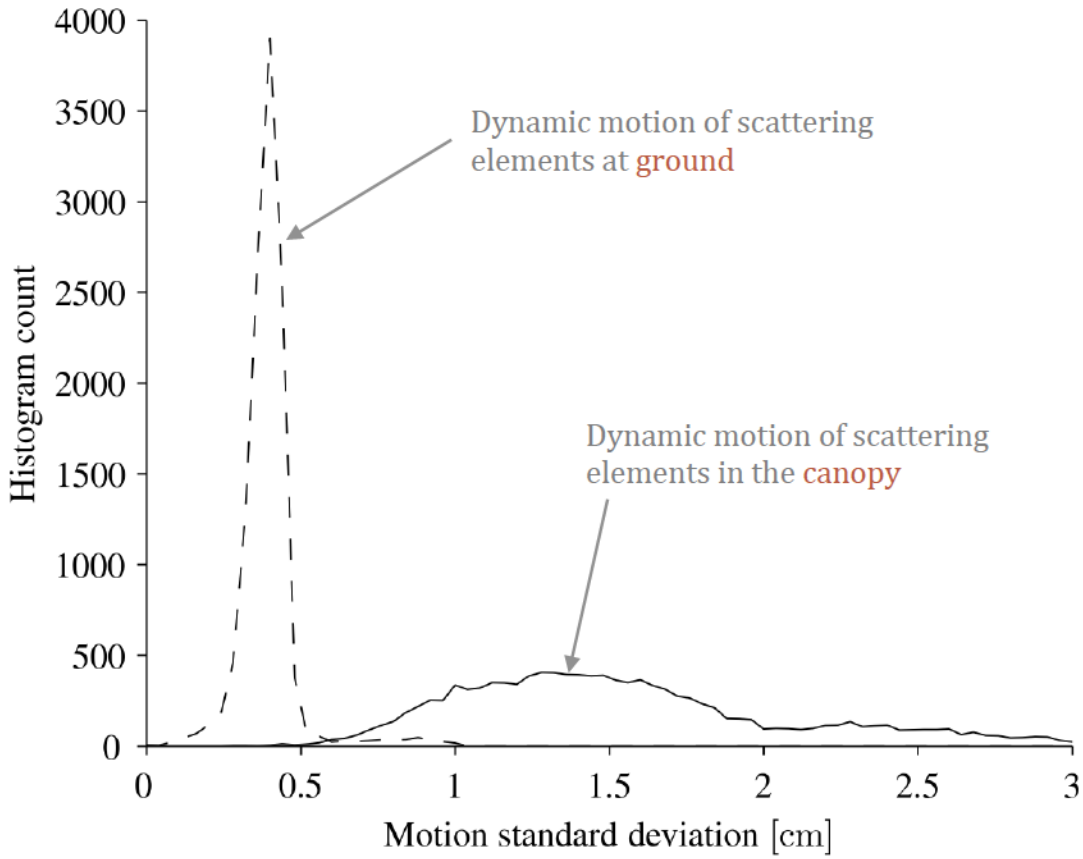
Comparison UAVSAR and LVIS

Forest height estimated from repeat-pass Pol-InSAR UAVSAR data and LVIS data



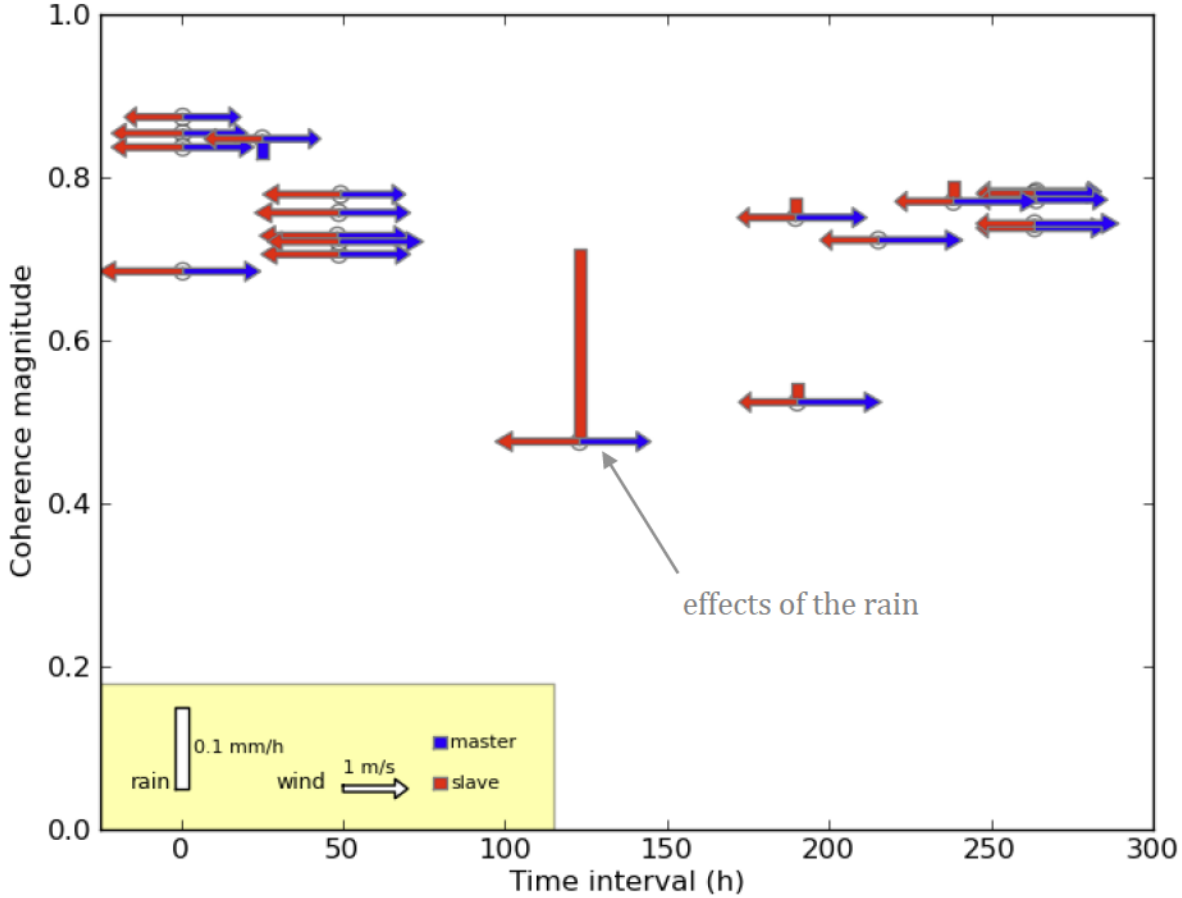
Estimation of temporal parameters

Effects of the wind on 2-day interval UAVSAR data



Comparison UAVSAR time series and weather data

Coherence, precipitation and wind data in Harvard Forest, MA



Conclusions

- Designed a new temporal decorrelation model that explains new properties of temporal decorrelation
- Model validated with L-band JPL/UAVSAR airborne data over boreal forests in Québec
- Proposed a model-based method to tackle the effects of temporal decorrelation (RMSE 20%). Method has been validated with the JPL/UAVSAR data over Harvard Forest, MA
- Attractive avenue for estimating forest parameters using single-baseline, repeat-pass polarimetric interferometry