Tackling temporal decorrelation in repeat-pass polarimetric interferometry

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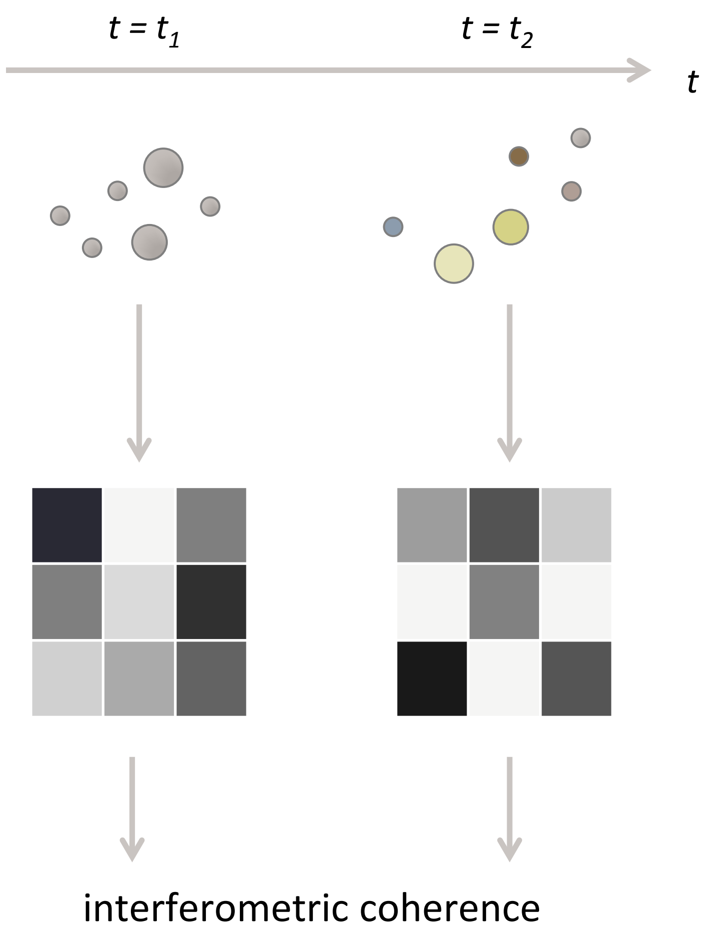
Outline

- Part I: Introduction to temporal decorrelation
  - What & why
  - Previous studies on temporal decorrelation
- Part II: Modeling temporal decorrelation
  - Zero-baseline case
  - RMoG model
- Part III: Tackling temporal decorrelation
  - Tree height estimation with repeat-pass PolInSAR data
  - Experiments with UAVSAR data

Part I
Introduction to temporal decorrelation

What is temporal decorrelation

- Modification of the interferometric coherence induced by changes of the target over time
- Temporal phenomena cause geometric (e.g., wind) or dielectric changes (e.g., rain)
- Interferometric coherence is calculated between two different targets at the acquisitions $t = t_1$ and $t = t_2$
- Changes are more likely to occur over longer temporal intervals

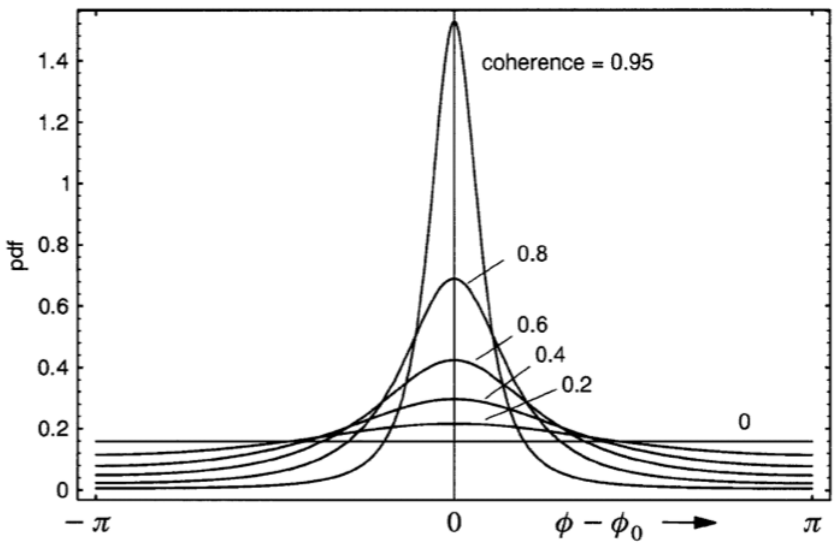


Effects of temporal decorrelation

- Temporal decorrelation typically decreases the coherence magnitude and increases the phase noise

$$\gamma = |\gamma| e^{j\varphi} = \frac{\langle s_1 s_2^* \rangle}{\sqrt{\langle s_1 s_1^* \rangle \langle s_2 s_2^* \rangle}}$$

- PolInSAR parameter retrieval is affected by large errors if temporal decorrelation is not properly taken into account

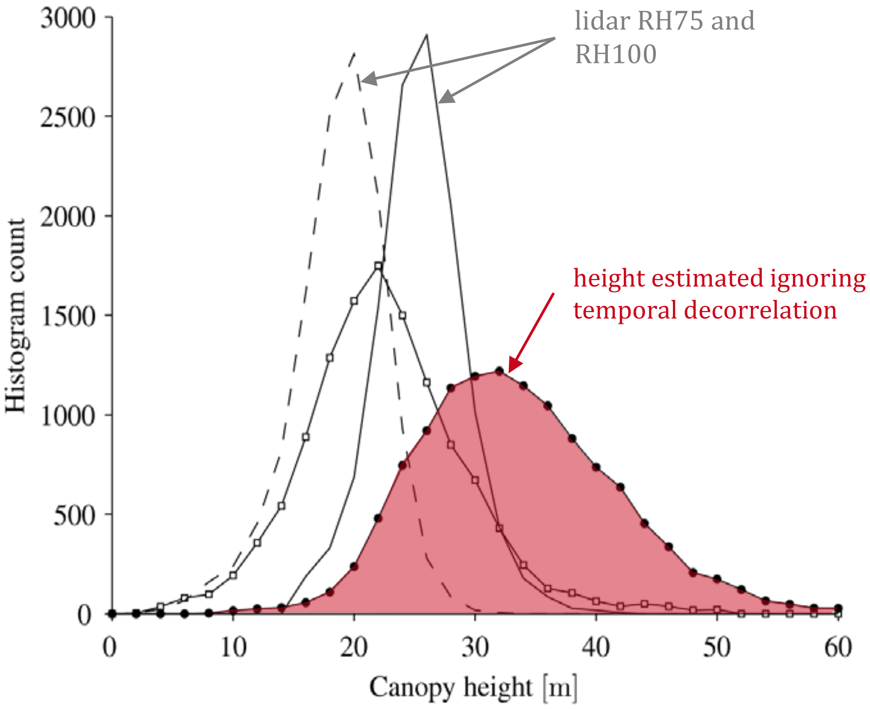


(plot from Bamler and Hartl, 1998)

Pol-InSAR and temporal decorrelation

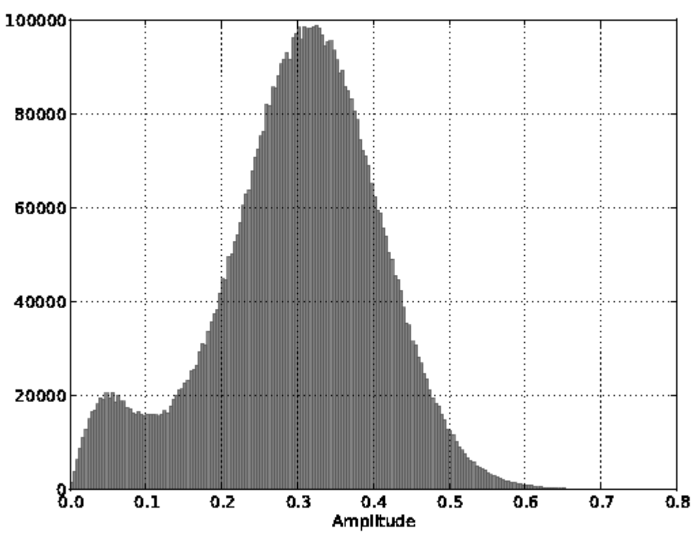
- Over forests, the estimated coherence is affected by volumetric and temporal decorrelation
- With the RVoG model canopy height is extracted from volumetric decorrelation
- In PolInSAR-RVoG canopy height retrieval, temporal decorrelation causes large bias and uncertainty

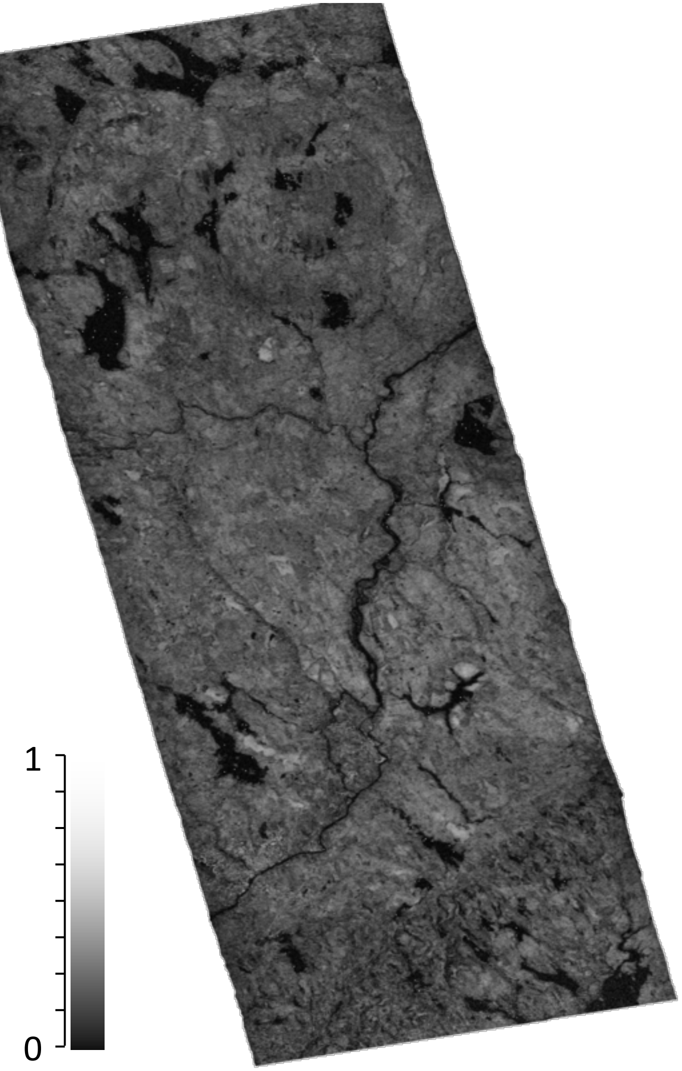
Canopy height estimated from JPL/UAVSAR data (Harvard Forest, MA)



Effects of temporal decorrelation

- ALOS/PALSAR coherence with pick around 0.3 (Howland, MN)
- Average tree height from LVIS lidar data is between 20 m and 25 m
- Tree heights estimated from PolInSAR coherence and RVoG model are large due to uncompensated temporal decorrelation





Previous solutions to Pol-InSAR TempDec

- Temporal decorrelation is accounted for by arbitrary correction terms
- RVoG model inversion with arbitrary temporal decorrelation is under-determined
- Correction terms are usually real-valued and estimated from external data
- Problems
  - Temporal decorrelation changes from acquisition to acquisition
  - Complex temporal phenomena are not taken into account

Common arbitrary correction terms for temporal decorrelation in the RVoG model

γ_t γ_t

$$\gamma_{g,v} = e^{jk_z z_g} \frac{\mu + \gamma_v e^{-jk_z z_g}}{\mu + 1}$$

γ_t

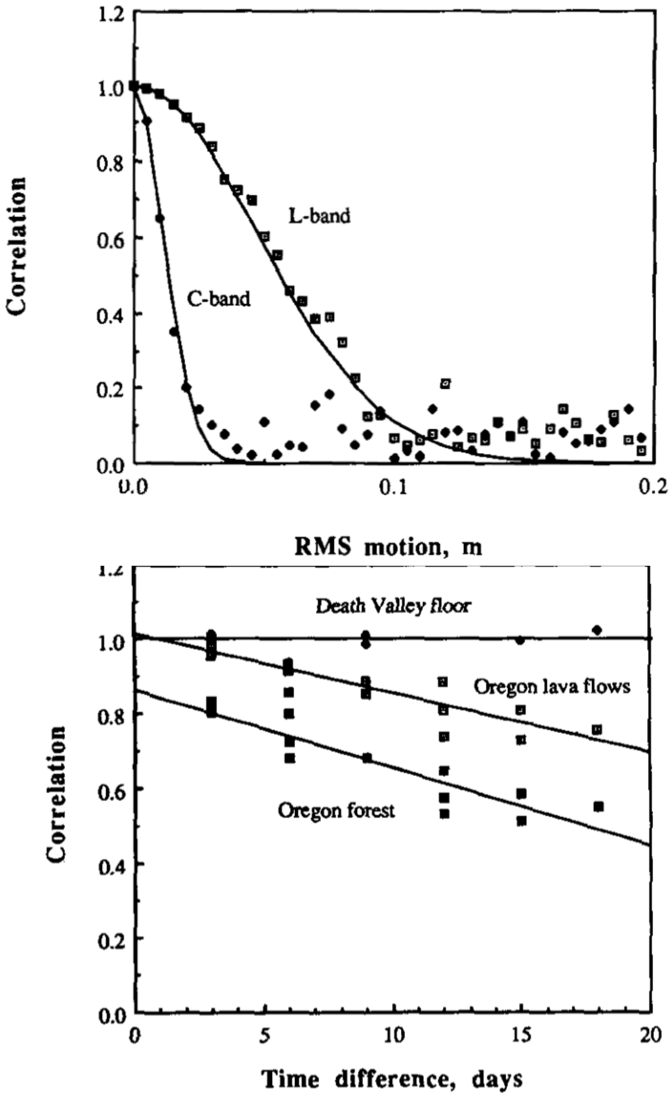
Past temporal decorrelation models

- Temporal decorrelation
  - exponential model (Zebker and Villasenor, 1992)

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

  - further extended to Brownian motion (Lombardini, 1994) and birth-and-death processes (Rocca, 2007)

- Additional desired features
  - temporal decorrelation and target structure
  - temporal decorrelation and polarization
  - complex-valued temporal decorrelation



(plots from Zebker and Villasenor, 1992)

Part II
Modeling temporal decorrelation

Temporal decorrelation model ($b_\perp = 0$)

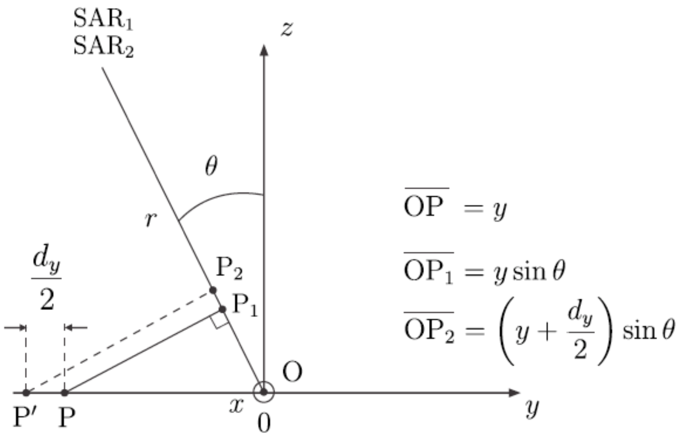
$$\gamma = |\gamma| e^{j\varphi} = \frac{\langle s_1 s_2^* \rangle}{\sqrt{\langle s_1 s_1^* \rangle \langle s_2 s_2^* \rangle}}$$

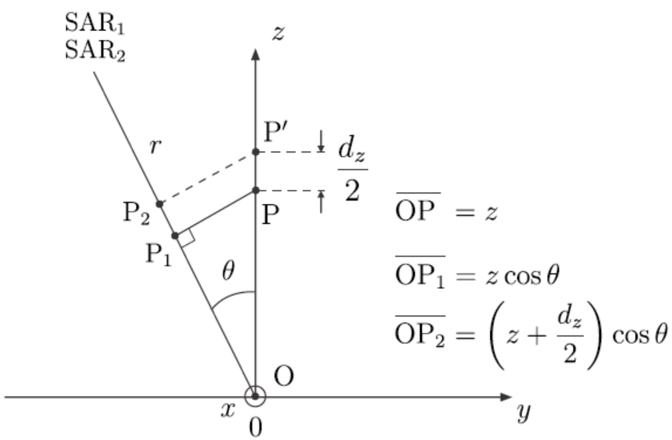
$$s_1 = \iiint f_1(x,y,z)\, \exp\{-j\frac{4\pi}{\lambda}(r + y\sin\theta - z\cos\theta)\} \cdot W(x,y)\, \mathrm{d}x\, \mathrm{d}y\, \mathrm{d}z + n_1 ,$$

$$s_2 = \iiint f_2(x,y,z)\, \exp\{-j\frac{4\pi}{\lambda}(r + y\sin\theta - z\cos\theta)\} \cdot W(x,y)\, \mathrm{d}x\, \mathrm{d}y\, \mathrm{d}z + n_2 ,$$

$$f_2(x,y,z) = f_1(x,y,z)\, \exp\left\{j\frac{4\pi}{\lambda}\left[\frac{d_y(z)}{2}\sin\theta + \frac{d_z(z)}{2}\cos\theta\right]\right\}$$

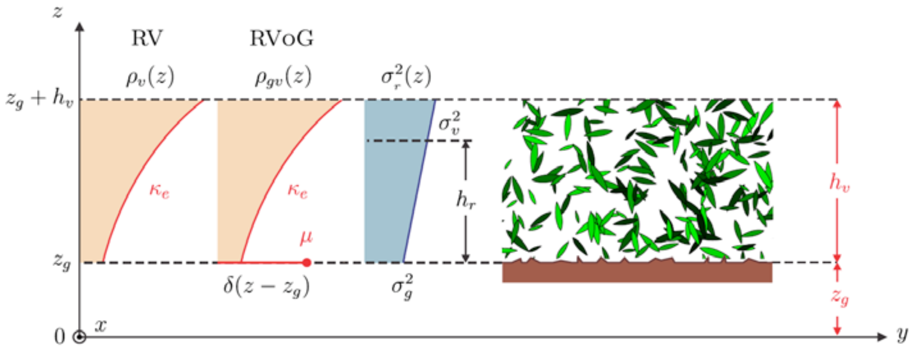
scatterer's displacement depends on initial vertical position





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

Temporal decorrelation model ($b_\perp = 0$)



- Temporal decorrelation depends on structure

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

structure function

temporal function

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

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

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

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

Temporal decorrelation model ($b_{\perp} = 0$)

- physical model
- closed-form expression
- 4 structure + 2 motion = 6 parameters

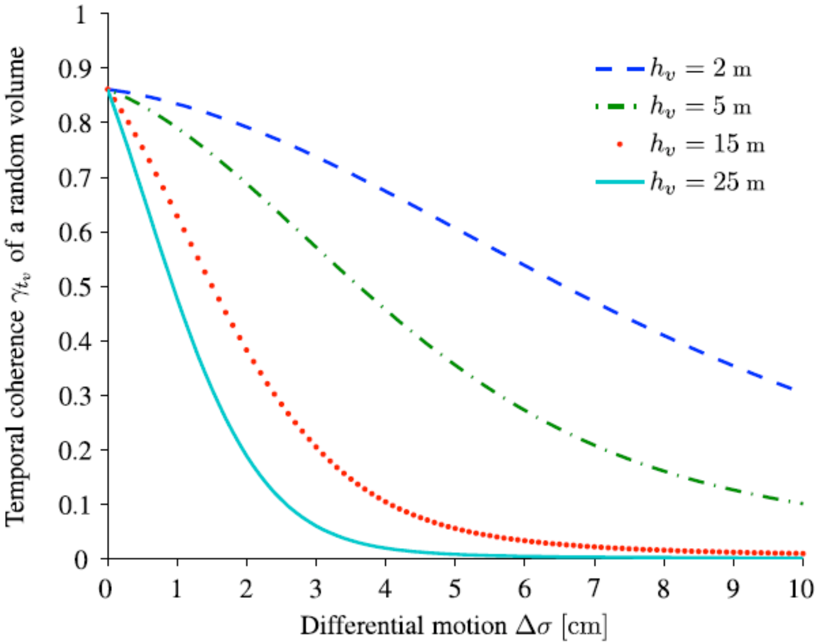
$$\gamma_{t_v} = \gamma_{t_g} \frac{p_1 \left[e^{(p_1+p_3)h_v} - 1 \right]}{(p_1 + p_3)\left(e^{p_1 h_v} - 1\right)}$$

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

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

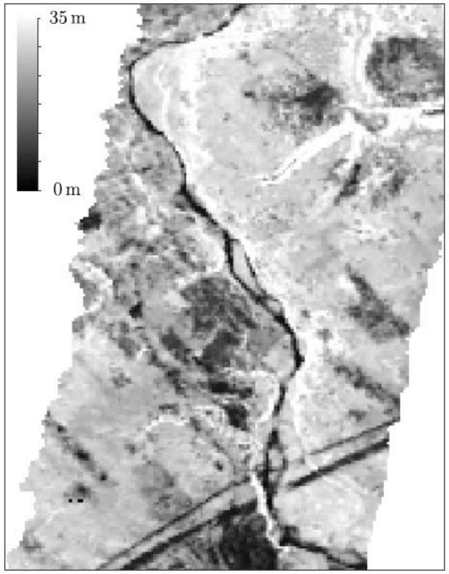
$$p_1 = \frac{2\kappa_e}{\cos\theta}, \qquad p_3 = -\frac{\Delta\sigma^2}{2h_r} \left(\frac{4\pi}{\lambda} \right)^2$$

temporal decorrelation
depends on canopy height

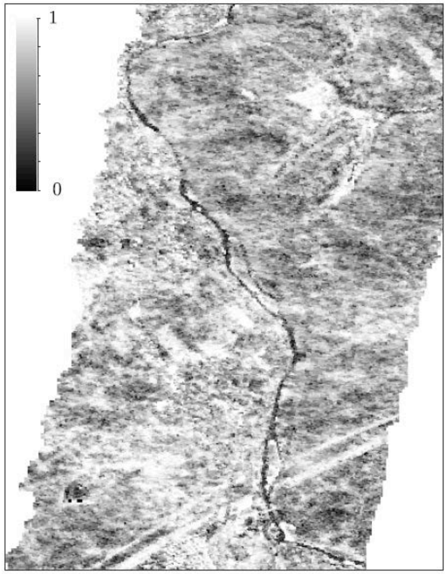


Validation of TempDec model ($b_{\perp} = 0$)

lidar canopy height (LVIS)

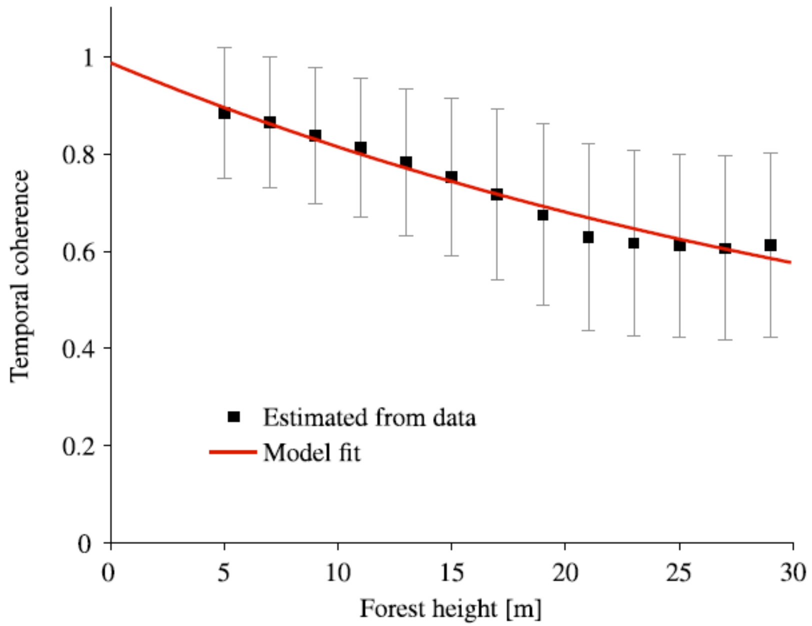


radar coherence (UAVSAR)



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

validation of dependence of temporal decorrelation on canopy height



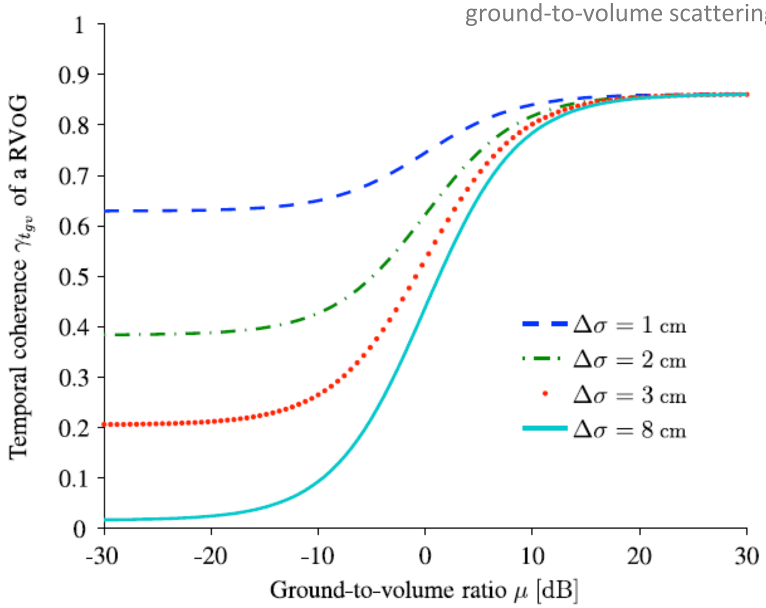
M. Lavalle, M. Simard and S. Hensley, "A temporal decorrelation model for polarimetric radar interferometers", IEEE TGRS 2012.

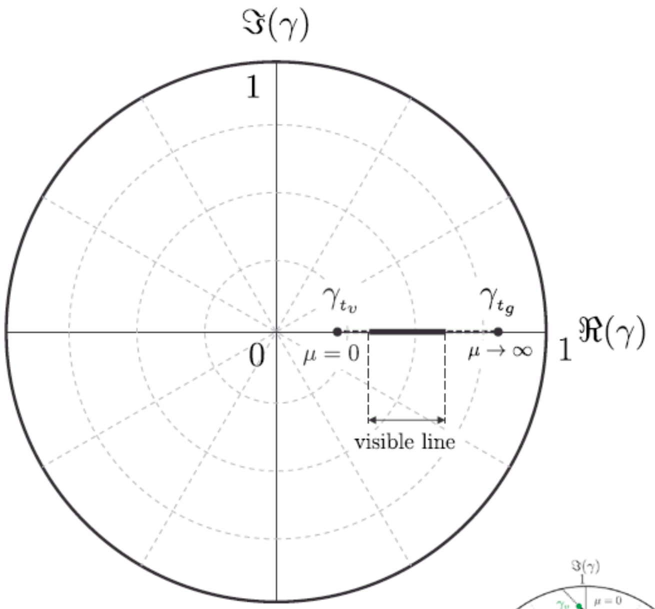
Temporal decorrelation model ($b_{\perp} = 0$)

$$\gamma_{tgv} = \frac{\mu \gamma_{tg} + \gamma_{tv}}{\mu + 1}$$

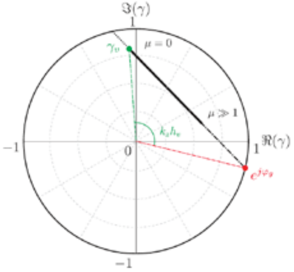
ground-to-volume scattering ratio

temporal decorrelation is sensitive to polarization ad has its own coherence locus





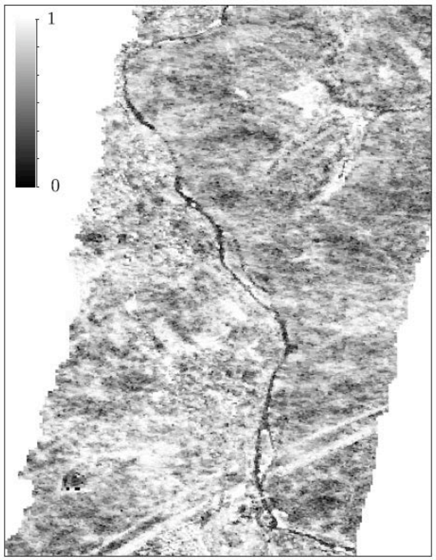
Similar concept as volume decorrelation locus



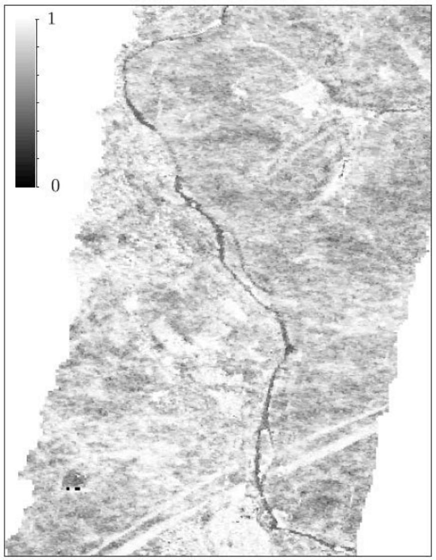
Validation of TempDec model ($b_{\perp} = 0$)

validation of dependence of temporal decorrelation on wave polarization

HV coherence



optimized high coherence



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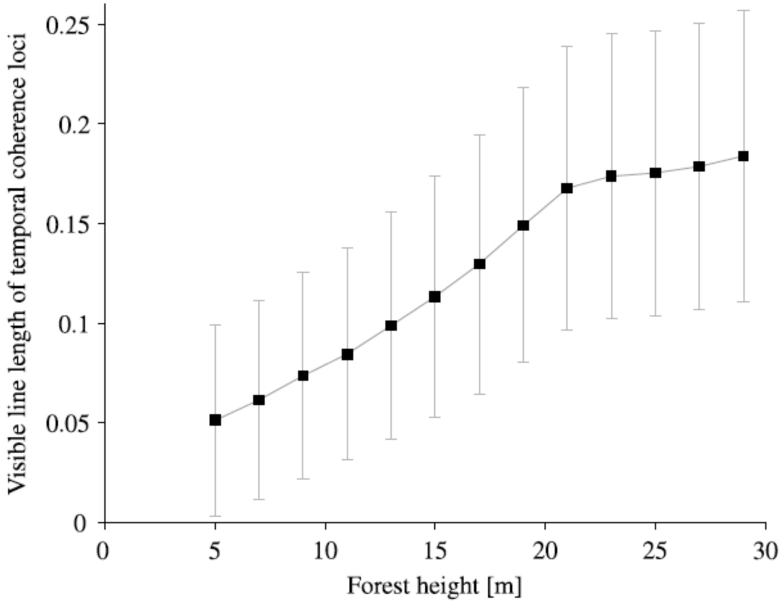

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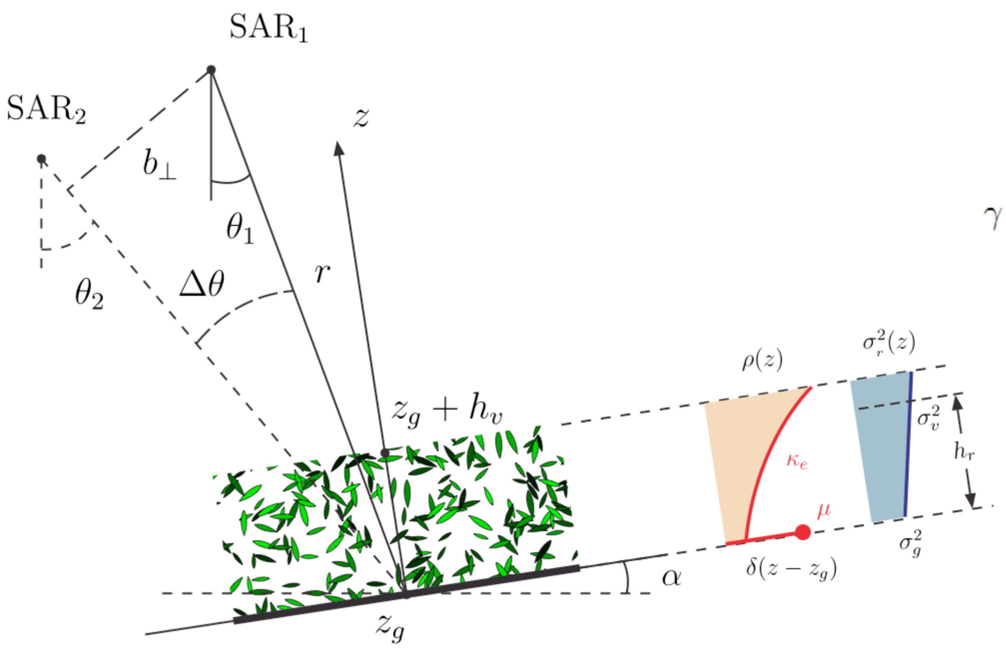
Temporal-volumetric decorr. model ($b_{\perp} \neq 0$)

General case of repeat-pass PolInSAR: arbitrary structure and temporal functions



phase term

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

temporal function

structure function

Random-motion-over-Ground (RMoG) model

- Structure function from RVoG model and temporal function from first-order expansion of Gaussian-statistic motion
- RMoG model: Closed-form expression of temporal-volumetric coherence
- 4 structural + 2 temporal = 6 model parameters
- Temporal and volumetric decorrelation are mixed and not separable

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

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

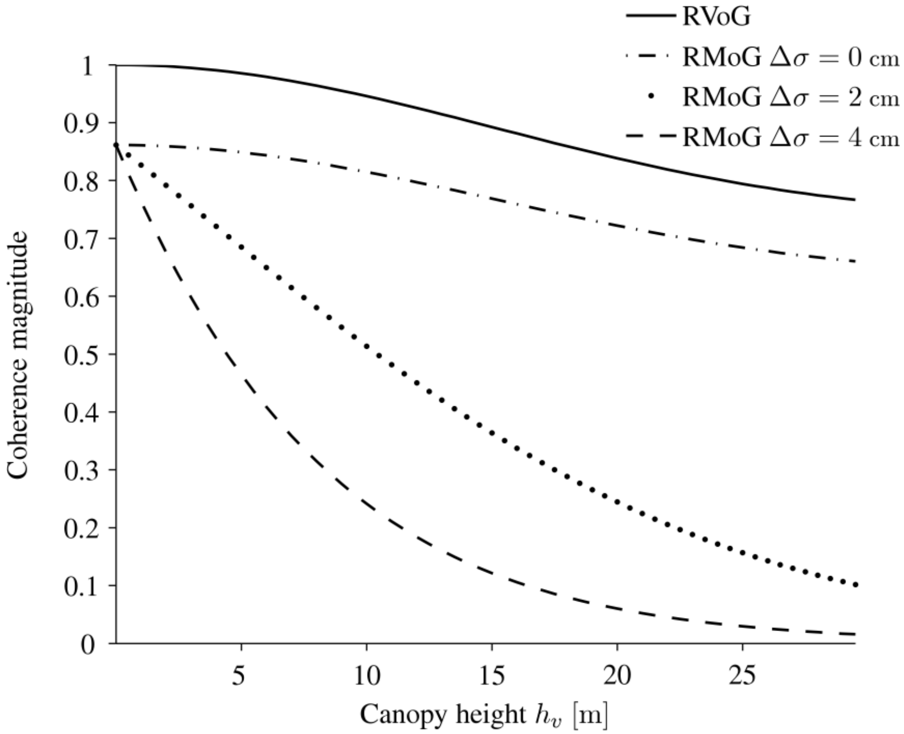
$$\gamma = e^{j\varphi_g}\,\frac{\mu\,\gamma_{t_g} + \gamma_{vt}\,e^{-j\varphi_g}}{\mu+1}$$

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

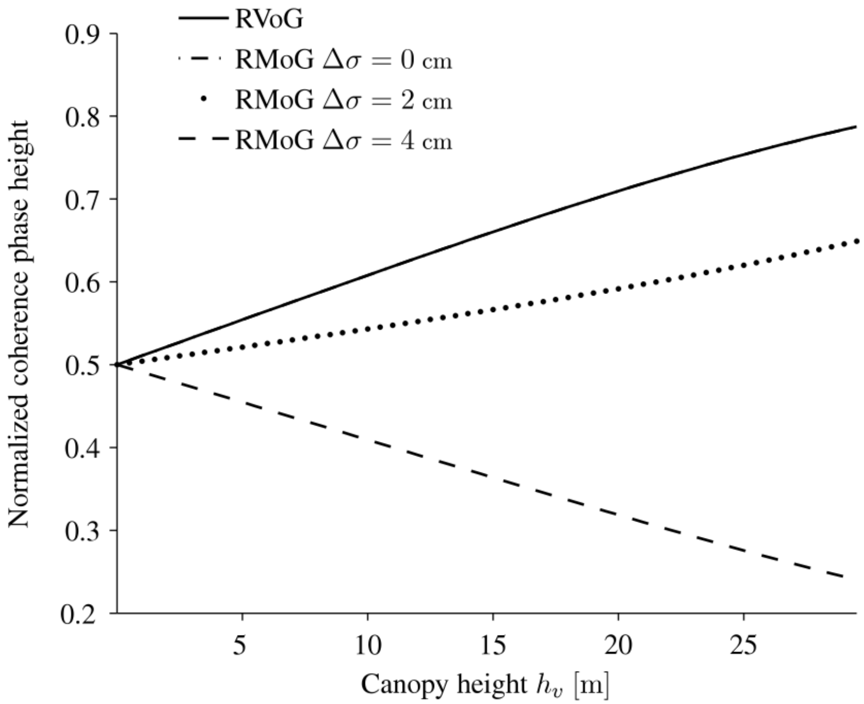
$$p_1 = \frac{2\kappa_e}{\cos(\theta-\alpha)}, \qquad p_2 = p_1 + jk_z, \qquad p_3 = -\frac{\Delta\sigma^2}{2h_r}\left(\frac{4\pi}{\lambda}\right)^2$$

RMoG model: Parametric analysis

coherence magnitude

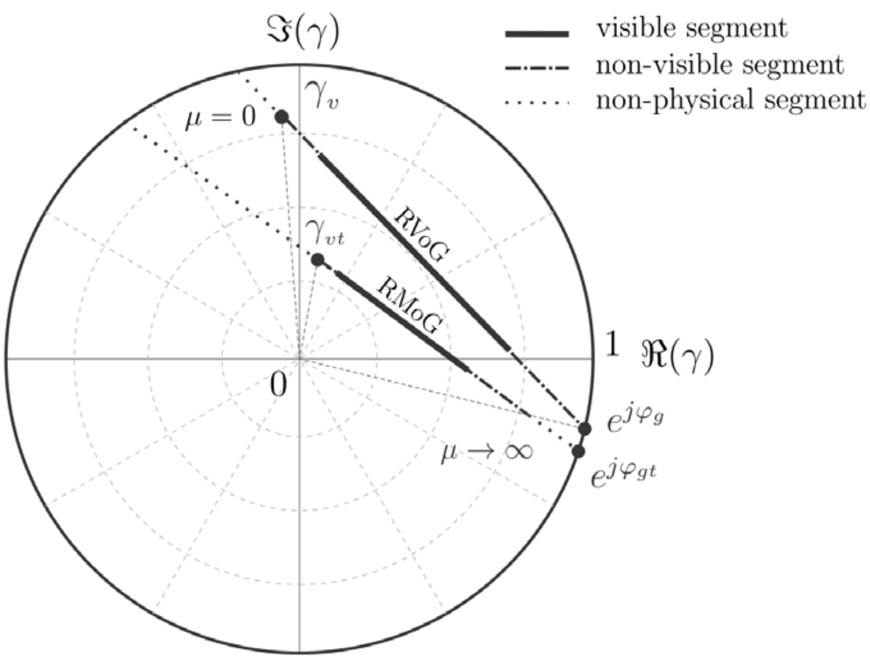


coherence phase



RMoG model: Coherence locus

- RMoG coherence locus shrinks and tilts with respect to RVoG coherence locus
- Intersection of RMoG line with unit circle is not ground topographic phase
- Canopy-dominated coherence changes magnitude and phase



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

$$\gamma_{vt} = e^{j\varphi_g} \gamma_{t_g} \frac{p_1 \left[e^{(p_2+p_3)h_v} - 1 \right]}{(p_2+p_3)\left(e^{p_1 h_v} - 1\right)} \qquad p_1 = \frac{2\kappa_e}{\cos(\theta - \alpha)}, \qquad p_2 = p_1 + jk_z, \qquad p_3 = -\frac{\Delta\sigma^2}{2h_r}\left(\frac{4\pi}{\lambda}\right)^2$$

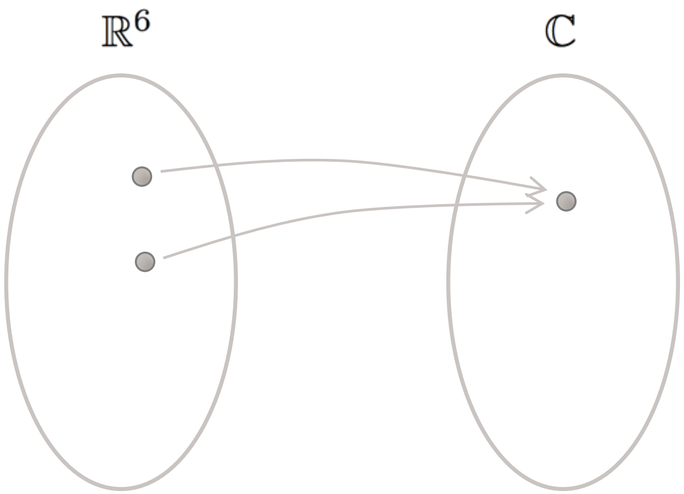
Part II

Tackling temporal decorrelation

RMoG forward problem

- Volumetric and temporal decorrelation effects are not separable
- temporal decorrelation depends on vegetation structure and wave polarization
- Invert the temporal-volumetric coherence without removing temporal decorrelation
- The RMoG model relates the coherence measured at different polarizations to structural and temporal parameters of forests

$$\gamma(p) = f_{RMoG}\begin{pmatrix} \text{canopy height} \\ \text{wave extinction} \\ \text{ground topography} \\ \text{ground-to-volume ratio} \\ \text{canopy scatterers motion} \\ \text{ground scatterers motion} \end{pmatrix}$$



$$f_{RMoG} : P \subset \mathbb{R}^6 \longrightarrow Q \subset \mathbb{C}$$

RMoG forward problem

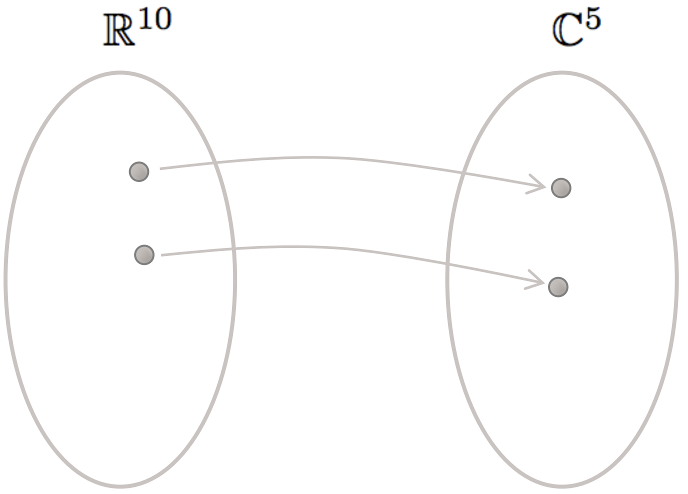
RMoG forward problem:

- 10 real model parameters balanced by 5 complex coherence observations

- Each coherence observations is associated with a different ground-to-volume ratio

- Codomain of this RMoG forward problem is the “ball” in the five-dimensional complex space

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



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

RMoG inverse strategy

RMoG inversion steps:

- 1. Coherence optimization (min/max phase center)
- 2. Unit circle intersection (estimation of approximate ground phase)
- 3. Multiple polarizations selection and least-square inversion

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

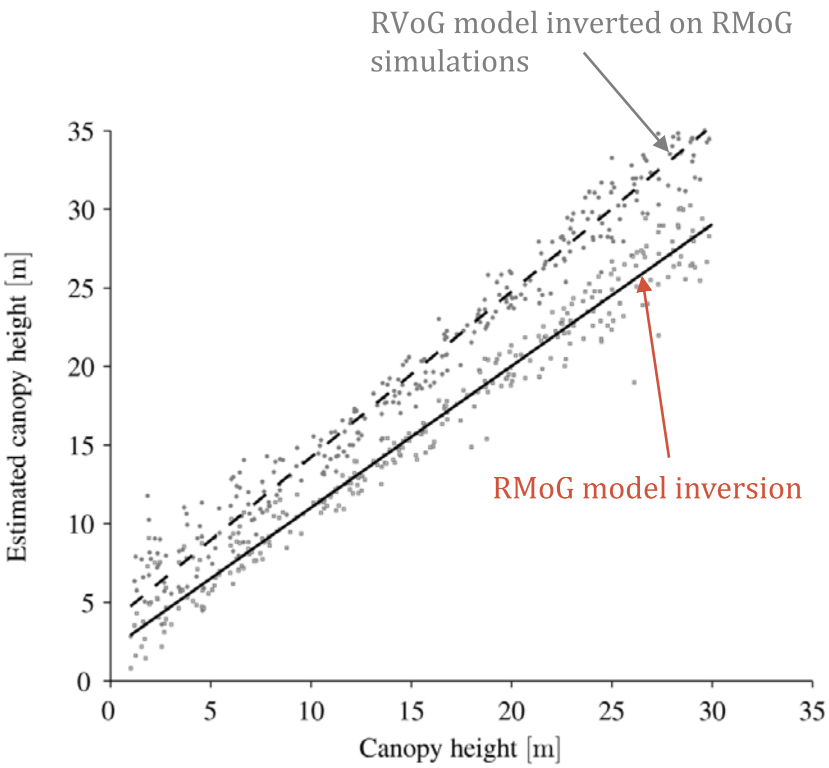
$$F = \sum_{i=1}^{5} \left| \gamma_i - \widehat{\gamma}_i \right|^2$$

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

$$\widehat{\gamma}_i = \widehat{\gamma}_1 + F_i \left(e^{j\varphi_{gt}} - \widehat{\gamma}_1 \right), \quad F_i = \frac{F_5}{4}(i-1) \quad i = 1, 2, \ldots, 5$$

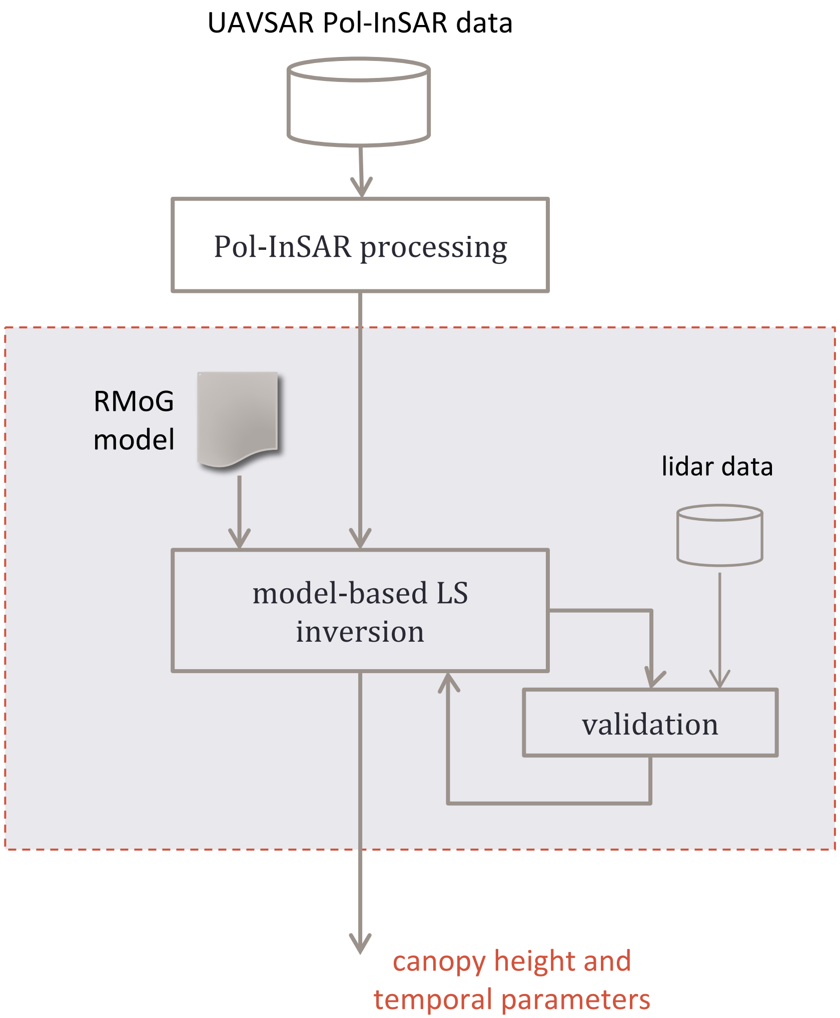
RMoG inversion on numerical simulations

- Numerical simulations
  - UAVSAR radar and acquisition geometry parameters
  - large range of values for forest and temporal parameters
- Average canopy height error in this example
  - RVoG model: RMSE 70% of total height
  - RMoG model: RMSE 20% of total height



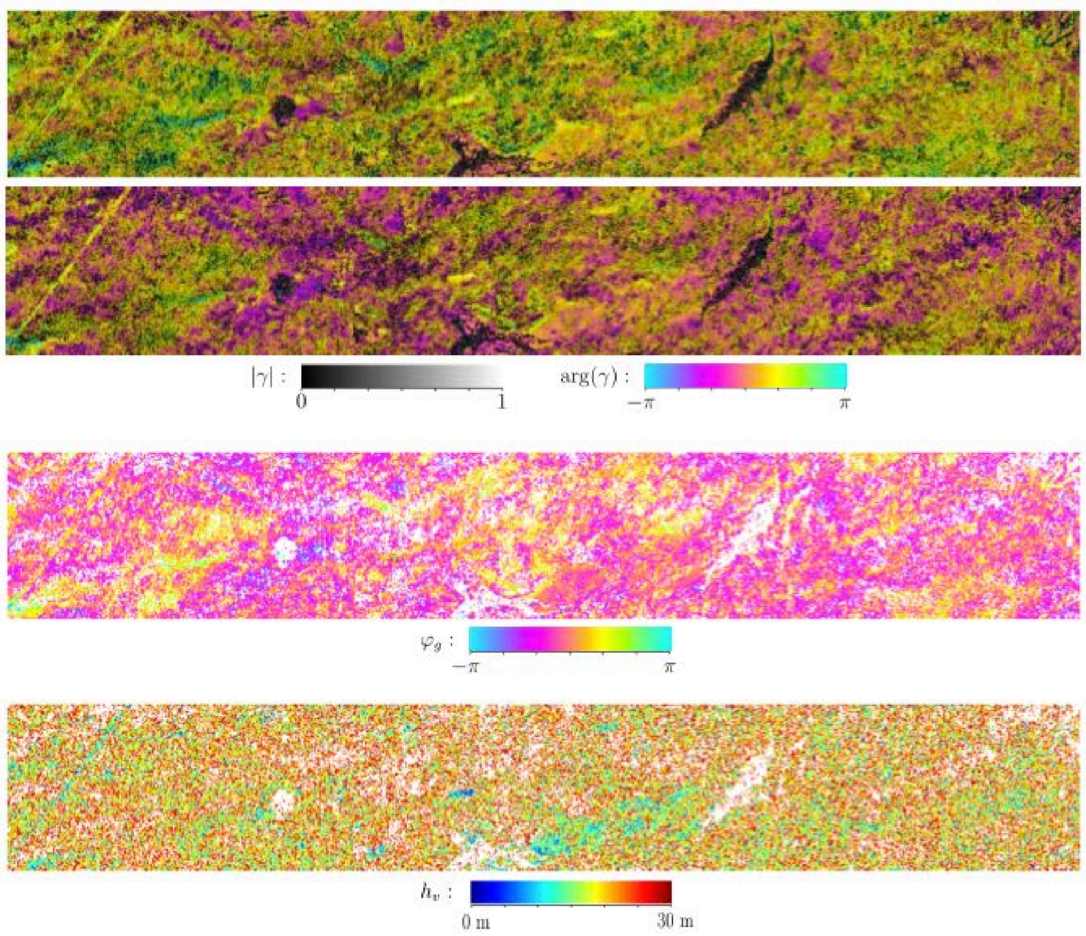
RMoG inversion on UAVSAR data

- Single-baseline, repeat-pass Pol-InSAR 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
- Validation of estimated canopy height with lidar LVIS data



Results: Tree height from Pol-InSAR UAVSAR data

Harvard Forest, MA, USA



Canopy-dominated coherence

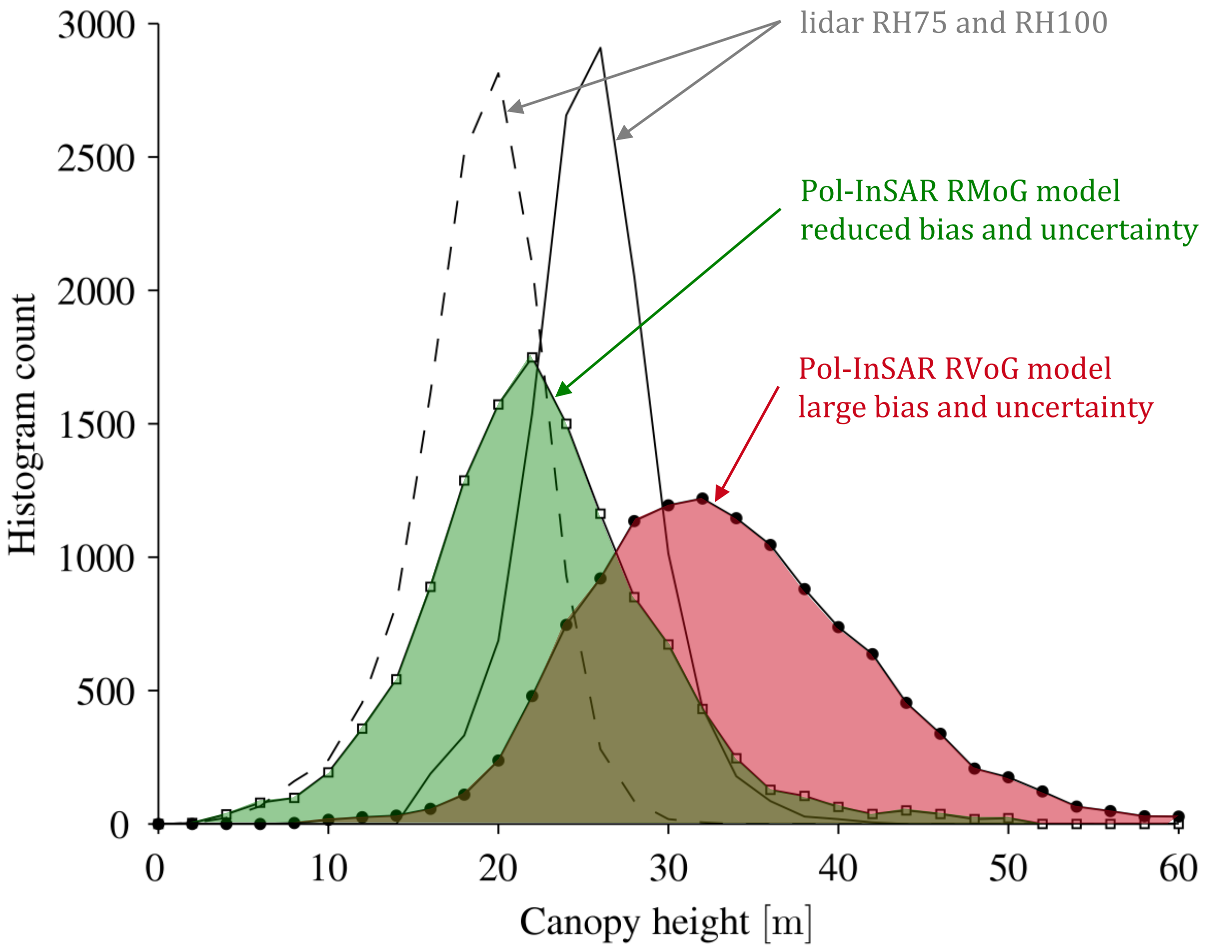
Ground-dominated coherence

Estimated ground topography

Estimated canopy height

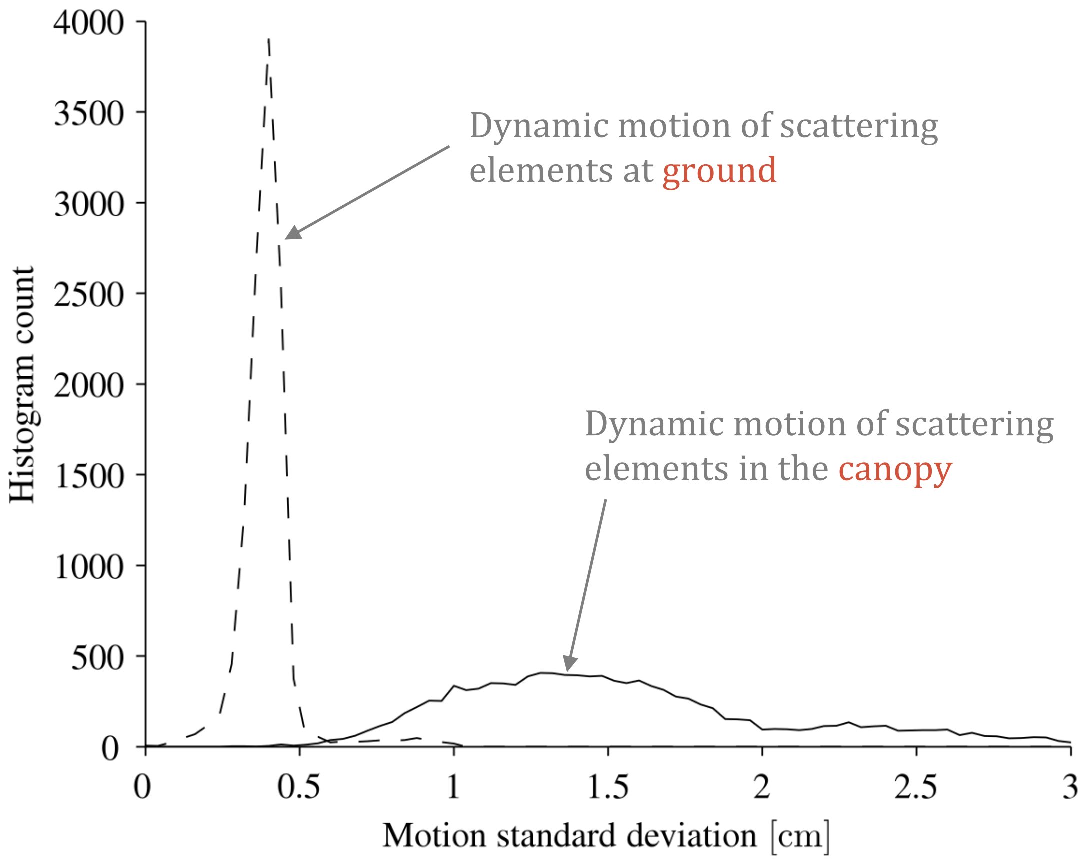
Results: Comparison UAVSAR and lidar

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



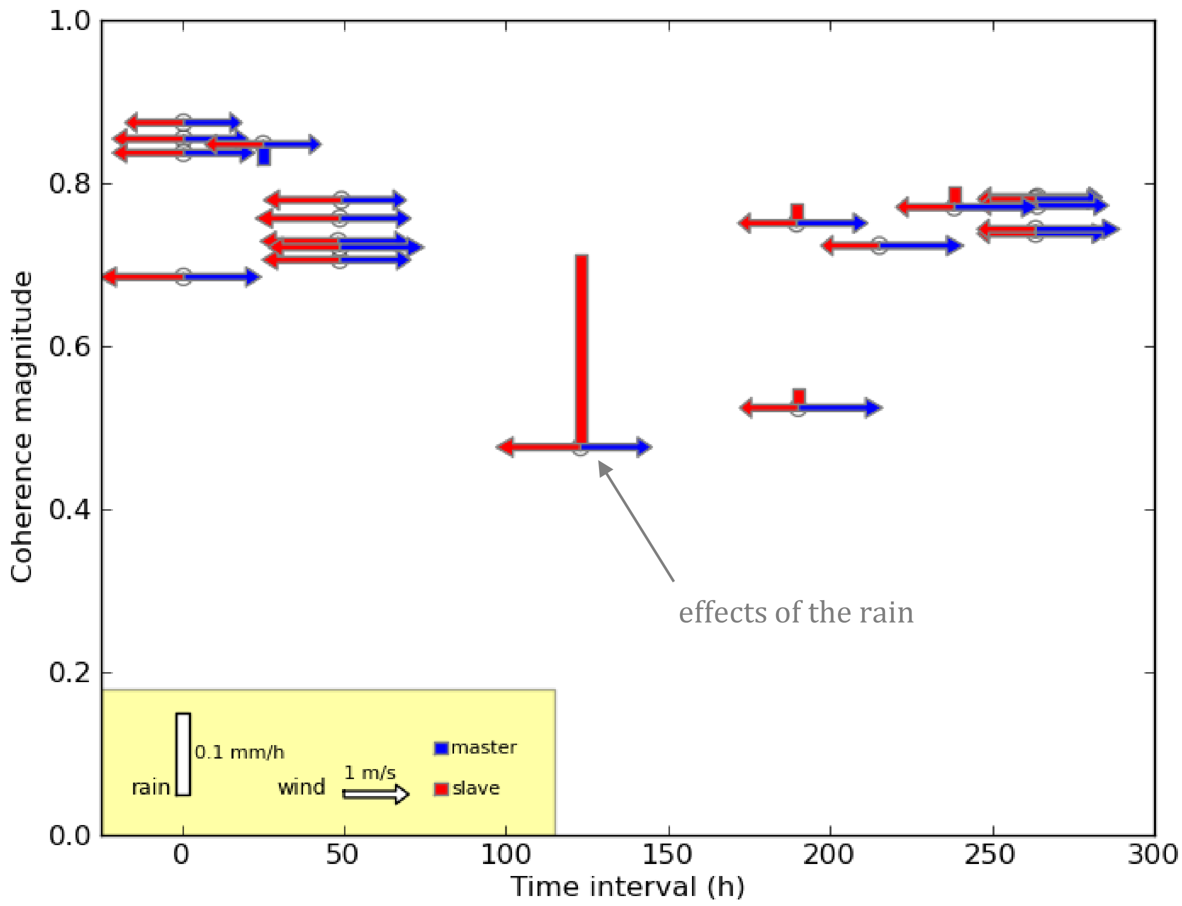
Results: Estimation of temporal paramters

Effects of wind on 2-day interval UAVSAR data



UAVSAR time series and weather data

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



Conclusions

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- In repeat-pass Pol-InSAR scenario temporal decorrelation may be modeled in order to extract ecosystem structural parameters
- The RMoG model is a physical model of temporal-volumetric decorrelation that enables potentially to extract 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 (ALOS-2, BIOMASS, SENTINEL-1, DESDynI)

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