Recent advances on InSAR temporal decorrelation: theory and observations using UAVSAR

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Outline

- Background and motivation
- Physical model of temporal decorrelation
- Model validation with JPL/UAVSAR data
- Application to forest height estimation
- Conclusions

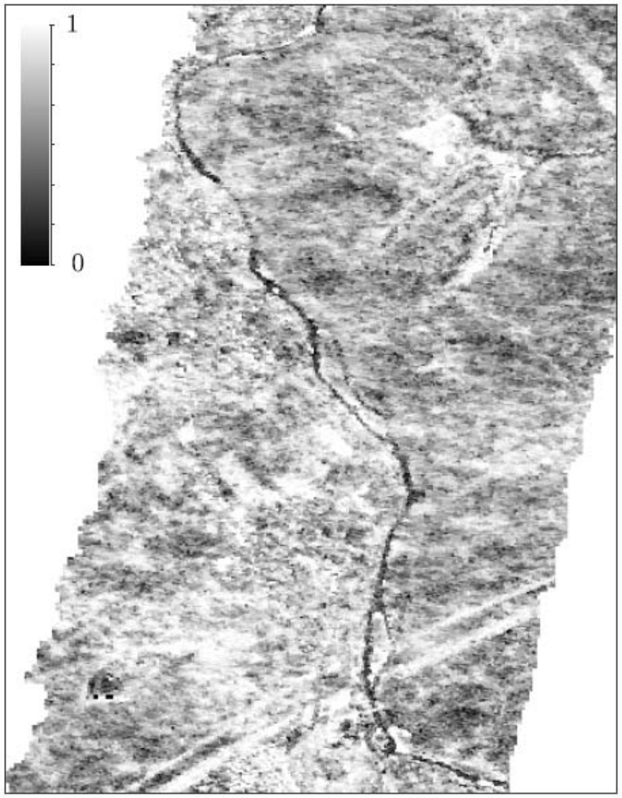
What we know about temporal decorrelation

- 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)

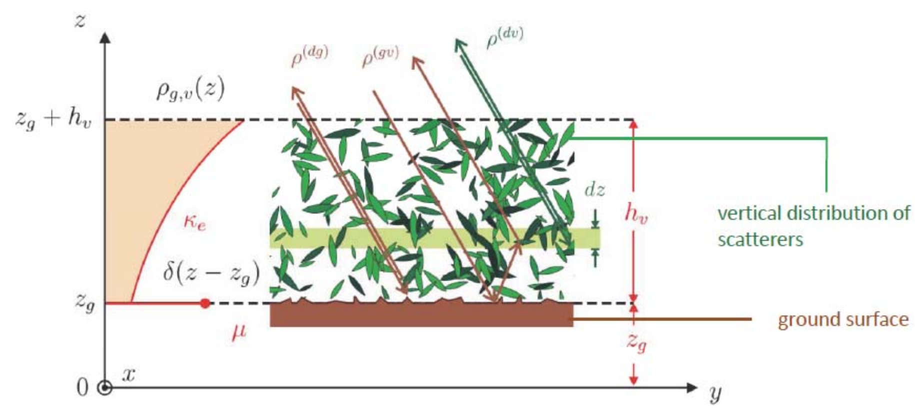
- Missing features
  - temporal decorrelation and target structure
  - temporal decorrelation and polarization
  - complex-valued temporal decorrelation



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

Why we need a refined model of temporal decorrelation

- InSAR over vegetation
  - estimation of vegetation structure
  - forest biomass



- Two-layer models of volume coherence
  - polarimetric InSAR
  - RVoG model (Cloude and Papathanassiou, 1998)

$$\gamma_{g,v} = \frac{\int \rho_{g,v}(z)\, e^{jk_z z}\, dz}{\int \rho_{g,v}(z)\, dz} = e^{j\varphi_g} \frac{\mu + \gamma_v e^{-j\varphi_g}}{\mu + 1}$$

$$\gamma_v = e^{j\varphi_g} \frac{p_1 \left[e^{p_2 h_v} - 1\right]}{p_2 \left(e^{p_1 h_v} - 1\right)}$$

$$p_1 = \frac{2\kappa_e}{\cos\theta} \qquad p_2 = \frac{2\kappa_e}{\cos\theta} + jk_z$$

- Temporal decorrelation
  - significantly affects the model-based inversion of RVoG model

Temporal decorrelation model

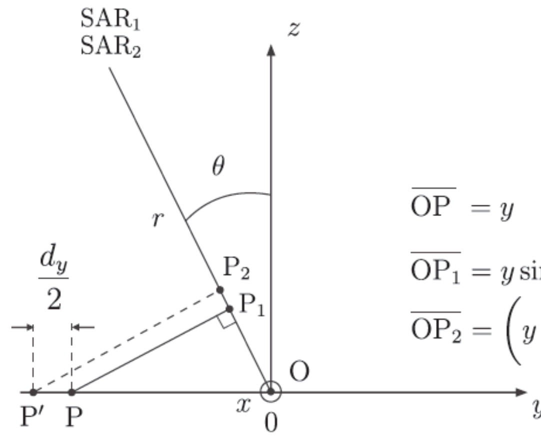
Temporal decorrelation model

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

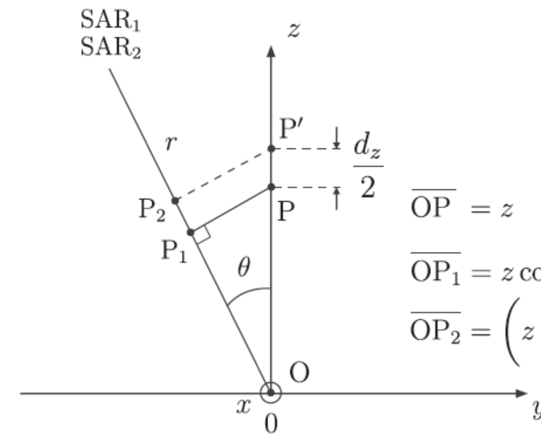
$$s_2 = \iiint f_2(x,y,z)\, \exp\{-j\frac{4\pi}{\lambda}(r + y\sin\theta - z\cos\theta)\} \cdot W(x,y)\, \mathrm{d}x\, \mathrm{d}y\, \mathrm{d}z + n_2\,,$$

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

scatterer's displacement depends on initial vertical position



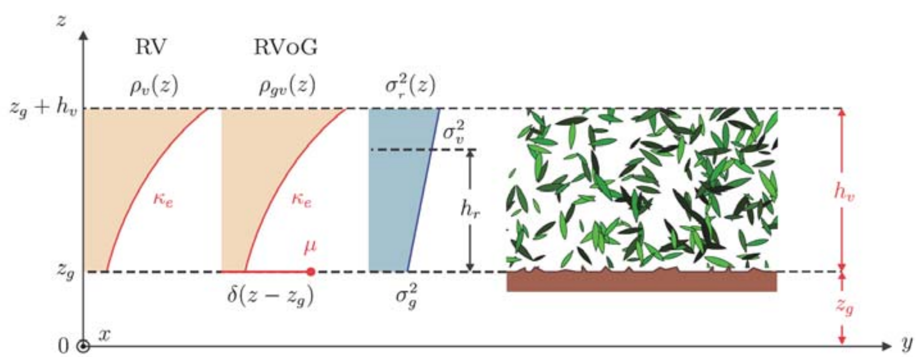
$$\overline{\mathrm{OP}} = y$$
$$\overline{\mathrm{OP}_1} = y\sin\theta$$
$$\overline{\mathrm{OP}_2} = \left(y + \frac{d_y}{2}\right)\sin\theta$$



$$\overline{\mathrm{OP}} = z$$
$$\overline{\mathrm{OP}_1} = z\cos\theta$$
$$\overline{\mathrm{OP}_2} = \left(z + \frac{d_z}{2}\right)\cos\theta$$

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

Temporal decorrelation model



- Temporal decorrelation depends on structure

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

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

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

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

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Temporal decorrelation model

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

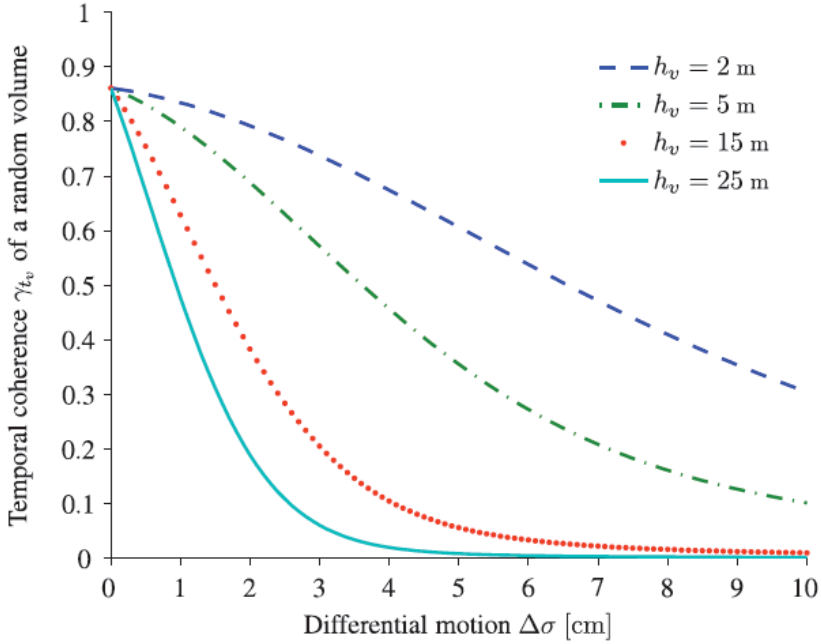
$$\gamma_{t_v} = \gamma_{t_g} \frac{p_1 \left[e^{(p_1+p_3)h_v} - 1 \right]}{(p_1+p_3)\left(e^{p_1 h_v} - 1\right)}$$

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

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

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

temporal decorrelation depends on canopy height



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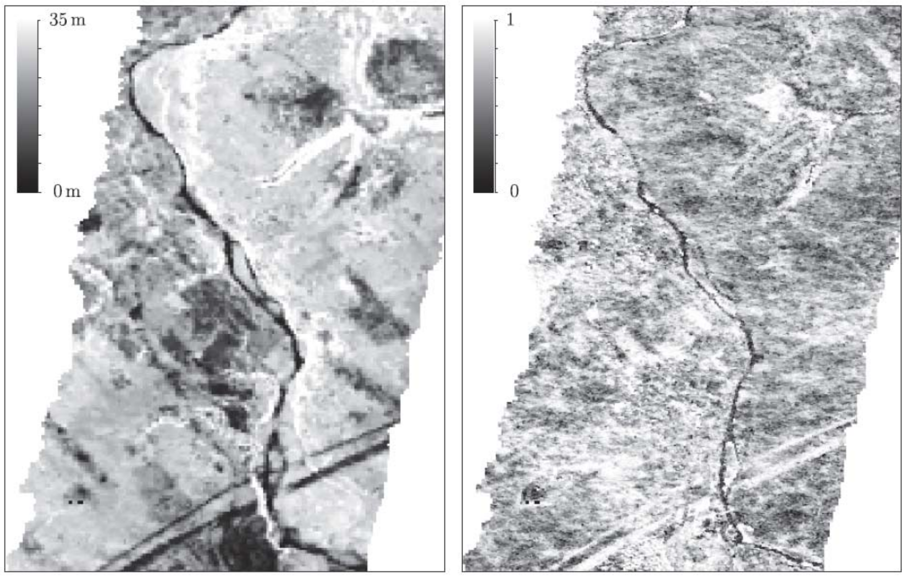
Validation of temporal decorrelation model

lidar canopy height (LVIS) radar coherence (UAVSAR)



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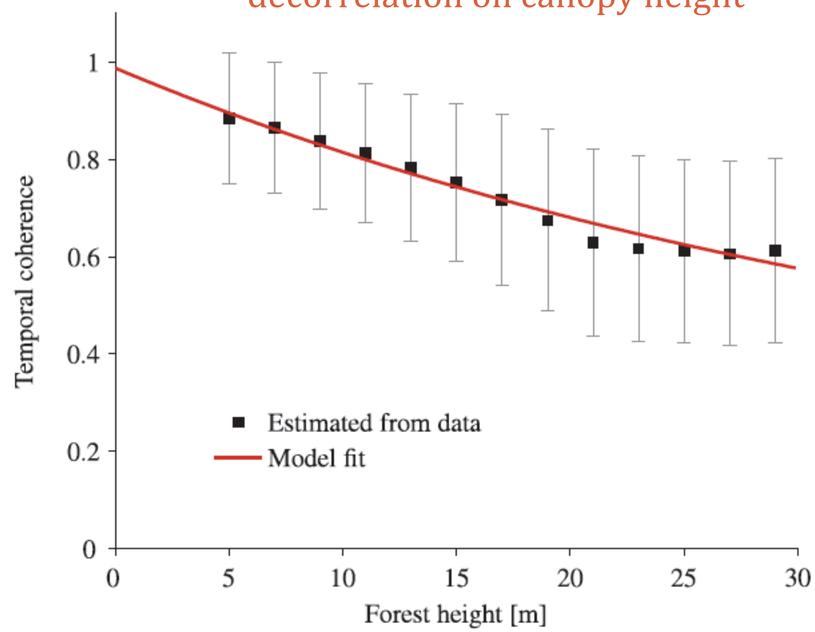
validation of dependence of temporal decorrelation on canopy height



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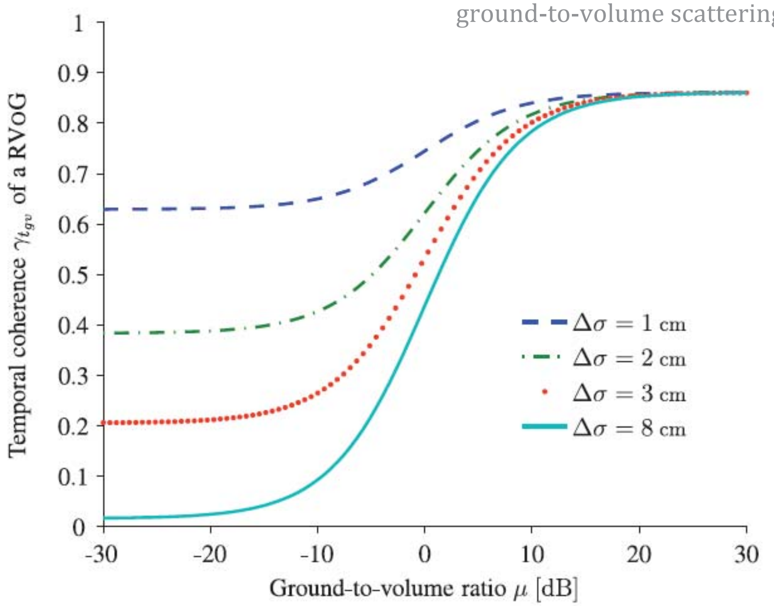
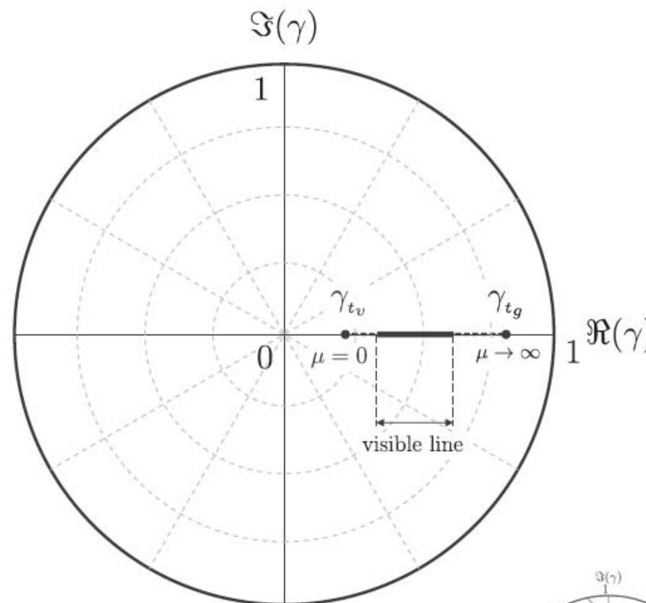
Temporal decorrelation model

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

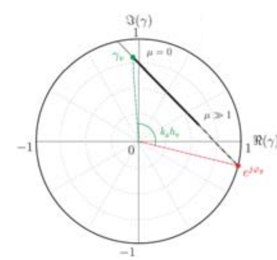
ground-to-volume scattering ratio

temporal decorrelation is sensitive to polarization





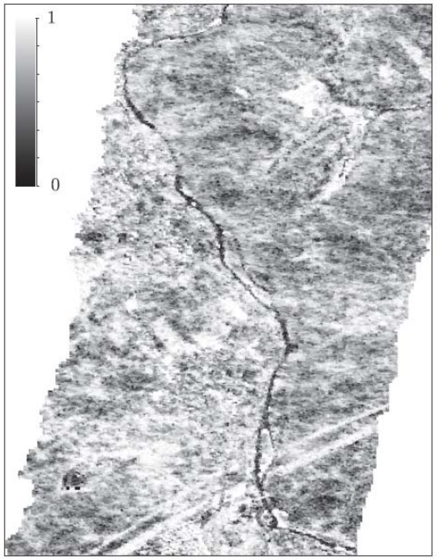
Similar concept of volume decorrelation loci

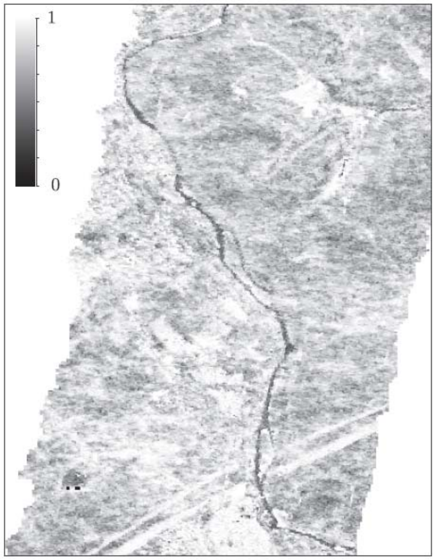


Validation of temporal decorrelation model

HV coherence

optimized high coherence





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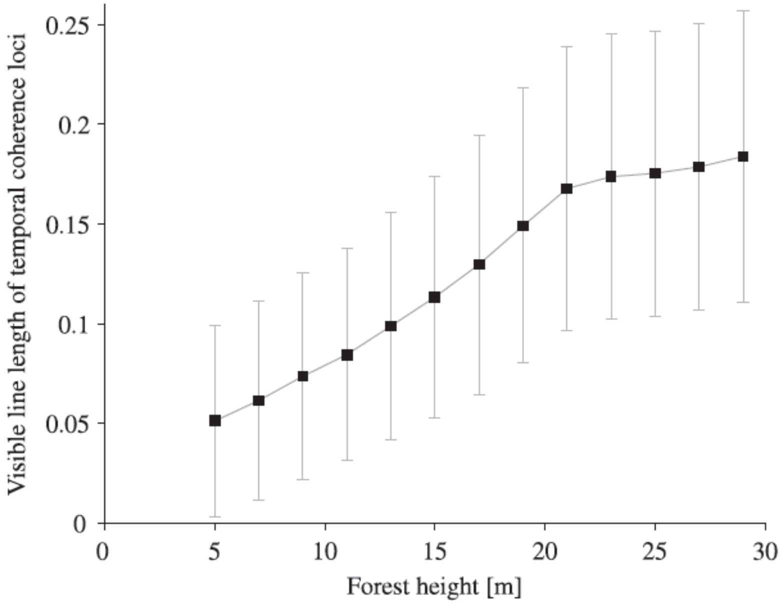
validation of dependence of temporal correlation on wave polarization



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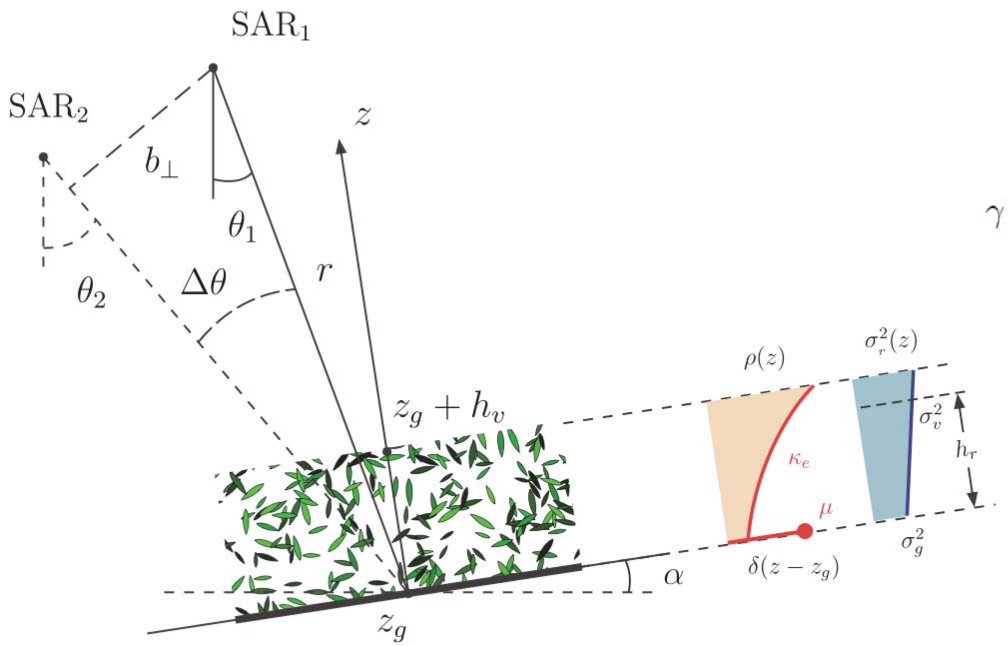
The general case:
temporal-volume decorrelation model

Temporal-volume decorrelation model



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

Temporal-volume decorrelation model

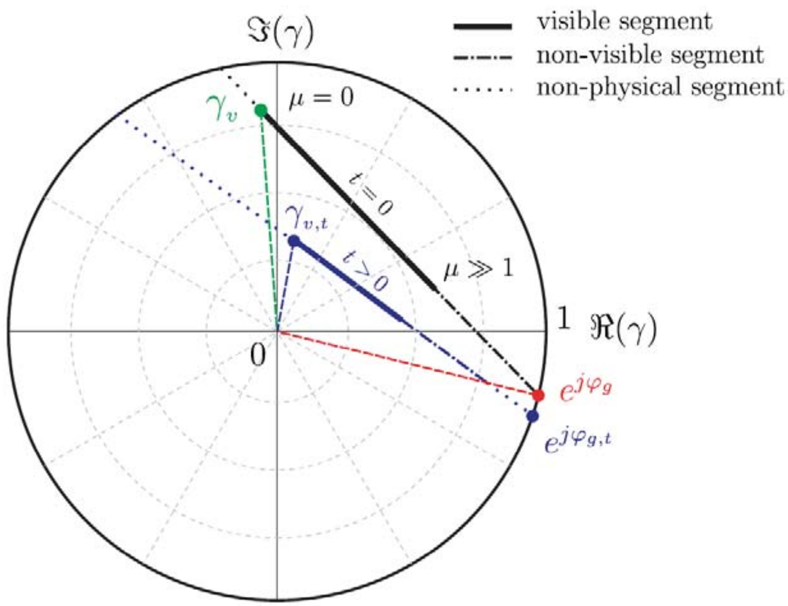
- Closed-form temporal-volume coherence model,
  4+2=6 model parameters

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

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

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

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

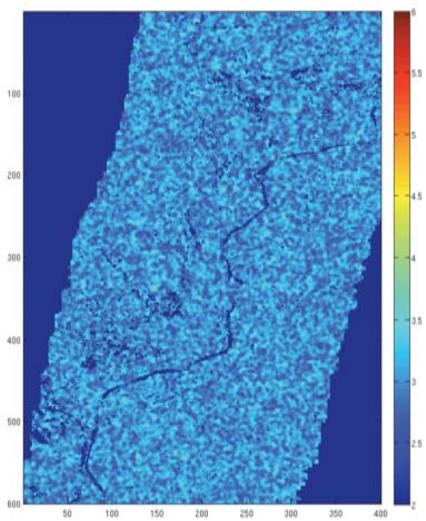


$$p_1 = \frac{2\kappa_e}{\cos(\theta-\alpha)}, \qquad p_2 = p_1 + jk_z, \qquad p_3 = -\frac{\Delta\sigma^2}{2h_r}\left(\frac{4\pi}{\lambda}\right)^2$$

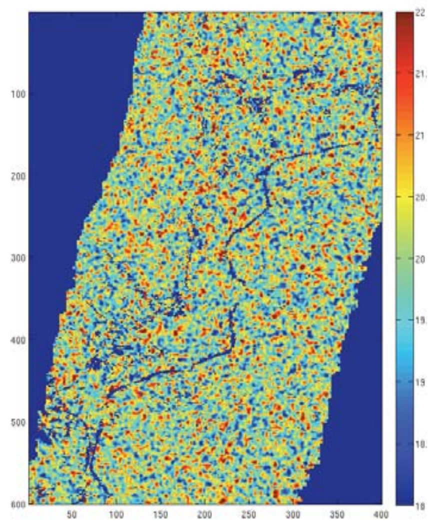
Application to forest height estimation

- Temporal-volume model inversion
  - real JPL/UAVSAR data with simulation of interferometric phase
  - temporal parameters, forest height, topography phase and ground-to-volume ratio from real data
  - Gaussian noise added

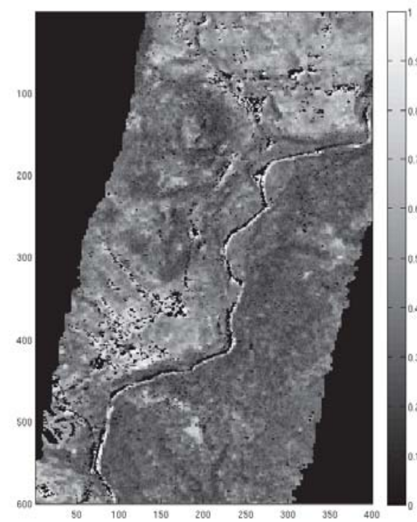
motion at ground-level [mm]



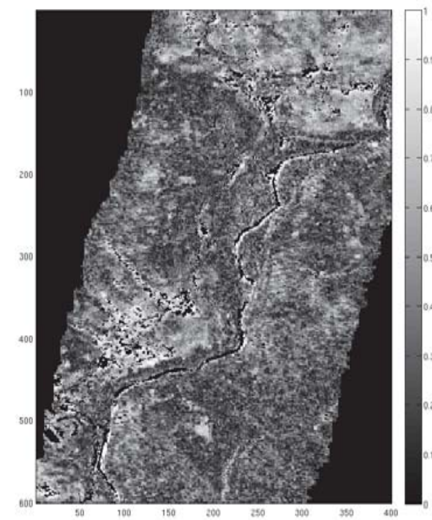
motion at canopy-level [mm]



coherence amplitude (high ground-to-volume ratio)

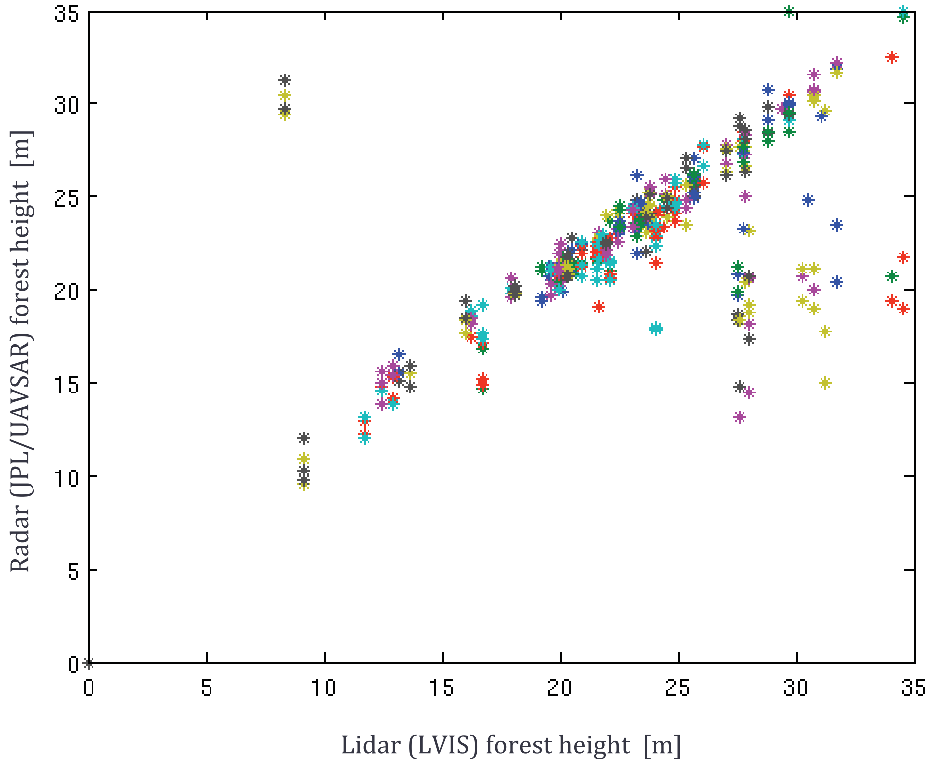


coherence amplitude (low ground-to-volume ratio)



Application to forest height estimation

Forest height estimated by a repeat-pass polarimetric radar interferometer



Consequences of our temporal decorrelation model

- temporal decorrelation depends on system wavelength through ground-to-volume ratio

$$\gamma_{t_{gv}} = \frac{\mu \gamma_{t_g} + \gamma_{t_v}}{\mu + 1} \qquad \gamma_{t_g} = \exp\left[-\frac{1}{2}\left(\frac{4\pi}{\lambda}\right)^2 \sigma_g^2\right]$$

- temporal decorrelation depends on full structure, including wave extinction

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

- product of temporal and volume coherence is not generally valid (→ definition of temporal factor)

$$\gamma \neq \gamma_t \gamma_v \longrightarrow \gamma = \alpha_t \gamma_v$$

- temporal factor is complex-valued and affects the scattering phase center position

Conclusions

- Designed a new temporal decorrelation model based on differential random motion
- Differential random motion explains new properties of temporal decorrelation
- Model validated with zero spatial baseline L-band JPL/UAVSAR airborne data
- Derived an invertible temporal-volume coherence model for forest canopies
- Attractive avenue for estimating forest parameters using repeat-pass polarimetric interferometry