Tackling temporal decorrelation in repeat-pass polarimetric interferometry

Marco Lavalle
marco.lavalle@jpl.nasa.gov

Jet Propulsion Laboratory, California Institute of Technology
• 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)
• Over forests, the estimated coherence is affected by \textit{volumetric} and \textit{temporal} decorrelation

• With the \textit{RVoG} model canopy height is extracted from volumetric decorrelation

• In PolInSAR-RVoG canopy height retrieval, temporal decorrelation causes large bias and uncertainty

\begin{figure}
\centering
\includegraphics[width=\textwidth]{canopy_height_graph.png}
\caption{Canopy height estimated from JPL/UAVSAR data (Harvard Forest, MA)}
\end{figure}
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

\[
\gamma_{g,v} = e^{jk_z z_g} \frac{\mu + \gamma_v e^{-jk_z z_g}}{\mu + 1}
\]
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 \((b_\perp = 0)\)

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

\[
s_1 = \iiint f_1(x, y, z) \exp\left\{-j\frac{4\pi}{\lambda} (r + y \sin \theta - z \cos \theta)\right\}
\cdot W(x, y) \, dx \, dy \, dz + n_1,
\]

\[
s_2 = \iiint f_2(x, y, z) \exp\left\{-j\frac{4\pi}{\lambda} (r + y \sin \theta - z \cos \theta)\right\}
\cdot W(x, y) \, dx \, dy \, dz + n_2,
\]

scatterer’s displacement depends on initial vertical position

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

- Temporal decorrelation depends on structure

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

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

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

\[
\sigma_r^2(z) = \sigma_g^2 + (\sigma_v^2 - \sigma_g^2) \frac{z - z_g}{h_r}
\]

\[
\Delta \sigma^2 = \sigma_v^2 - \sigma_g^2,
\]
Temporal decorrelation model \((b_\perp = 0)\)

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

\[
\gamma_{t_v} = \gamma_{t_g} \frac{p_1 \left[ e^{(p_1+p_3)h_v} - 1 \right]}{(p_1 + p_3) \left( e^{p_1h_v} - 1 \right)}
\]

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

\[
\gamma_{t_{g,v}} = \frac{\mu \gamma_{t_g} + \gamma_{t_v}}{\mu + 1}
\]

\[
p_1 = \frac{2\kappa_e}{\cos \theta}, \quad p_3 = -\frac{\Delta \sigma^2}{2h_r} \left( \frac{4\pi}{\lambda} \right)^2
\]
Validation of TempDec model ($b_\perp = 0$)

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

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

temporal decorrelation is sensitive to polarization and has its own coherence locus.

Ground-to-volume scattering ratio

Similar concept as volume decorrelation locus.
Validation of TempDec model ($b_\perp = 0$)

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

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

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

\[
\gamma = \frac{\int \rho(z) e^{j k z} \exp \left[ -\frac{1}{2} \left( \frac{4\pi}{\lambda} \right)^2 \sigma^2(z) \right] \, dz}{\int \rho(z) \, dz}
\]

structure function

phase term

temporal 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**

\[
\gamma_{vt} = e^{j\varphi_g} \gamma_{tg} = \frac{p_1 \left[ e^{(p_2+p_3)h_v} - 1 \right]}{(p_2 + p_3) \left( e^{p_1h_v} - 1 \right)}
\]

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

\[
\gamma = e^{j\varphi_g} \frac{\mu \gamma_{tg} + \gamma_{vt} e^{-j\varphi_g}}{\mu + 1}
\]

\[
p_1 = \frac{2\kappa_e}{\cos(\theta - \alpha)}, \quad p_2 = p_1 + jk_z, \quad p_3 = -\frac{\Delta \sigma^2}{2h_r} \left( \frac{4\pi}{\lambda} \right)^2
\]
RMoG model: Parametric analysis

**Coherence Magnitude**

- RVoG
- RMoG $\Delta \sigma = 0 \text{ cm}$
- RMoG $\Delta \sigma = 2 \text{ cm}$
- RMoG $\Delta \sigma = 4 \text{ cm}$

**Coherence Phase**

- RVoG
- RMoG $\Delta \sigma = 0 \text{ cm}$
- RMoG $\Delta \sigma = 2 \text{ cm}$
- RMoG $\Delta \sigma = 4 \text{ cm}$

Canopy height $h_v$ [m]

Normalized 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

\[
\gamma = e^{j\varphi_g} \frac{\mu \gamma_{tg} + \gamma_{vt} e^{-j\varphi_g}}{\mu + 1}
\]

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

\[
p_1 = \frac{2K_e}{\cos(\theta - \alpha)}, \quad p_2 = p_1 + jk_z, \quad p_3 = -\frac{\Delta \sigma^2}{2h_r} \left(\frac{4\pi}{\lambda}\right)^2
\]
Part II
Tackling temporal decorrelation
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.

\[ \gamma(p) = f_{RMoG} \]

- canopy height
- wave extinction
- ground topography
- ground-to-volume ratio
- canopy scatterers motion
- ground scatterers motion

\[ f_{RMoG}: P \subset \mathbb{R}^6 \rightarrow Q \subset \mathbb{C} \]
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
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

\[
\begin{align*}
\hat{\gamma}_1 e^{-j\varphi_{gt}} &= e^{j(\varphi_g - \varphi_{gt})} \frac{\mu_1 \gamma_{tg} + \gamma_{vt} e^{-j\varphi_g}}{\mu_1 + 1} \\
\hat{\gamma}_2 e^{-j\varphi_{gt}} &= e^{j(\varphi_g - \varphi_{gt})} \frac{\mu_2 \gamma_{tg} + \gamma_{vt} e^{-j\varphi_g}}{\mu_2 + 1} \\
\hat{\gamma}_3 e^{-j\varphi_{gt}} &= e^{j(\varphi_g - \varphi_{gt})} \frac{\mu_3 \gamma_{tg} + \gamma_{vt} e^{-j\varphi_g}}{\mu_3 + 1} \\
\hat{\gamma}_4 e^{-j\varphi_{gt}} &= e^{j(\varphi_g - \varphi_{gt})} \frac{\mu_4 \gamma_{tg} + \gamma_{vt} e^{-j\varphi_g}}{\mu_4 + 1} \\
\hat{\gamma}_5 e^{-j\varphi_{gt}} &= e^{j(\varphi_g - \varphi_{gt})} \frac{\mu_5 \gamma_{tg} + \gamma_{vt} e^{-j\varphi_g}}{\mu_5 + 1}
\end{align*}
\]

\[
F = \sum_{i=1}^{5} |\gamma_i - \hat{\gamma}_i|^2
\]

\[
\gamma_i = e^{j\varphi_g} \frac{\mu_i \gamma_{tg} + \gamma_{vt} e^{-j\varphi_g}}{\mu_i + 1}
\]

\[
\hat{\gamma}_i = \hat{\gamma}_1 + F_i (e^{j\varphi_{gt}} - \hat{\gamma}_1), \quad F_i = \frac{F_5}{4} (i - 1) \quad i = 1, 2, ..., 5
\]
- 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 generate 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

- Pol-InSAR RVoG model: large bias and uncertainty
- Pol-InSAR RMoG model: reduced bias and uncertainty
- lidar RH75 and RH100

Histogram count vs. Canopy height [m]
Results: Estimation of temporal parameters

Effects of wind on 2-day interval UAVSAR data

- Dynamic motion of scattering elements at ground
- Dynamic motion of scattering elements in the canopy
UAVSAR time series and weather data

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

effects of the rain
Conclusions

- 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).

More info: marco.lavalle@jpl.nasa.gov
http://www.caltech.edu/~mlavalle/
http://uavsar.jpl.nasa.gov