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

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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)

- 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
  - 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
  - Hainsek, 2009
  - Lavalle, 2010
  - Garestier, 2010
  - Lopez-Martinez, 2010
  - Tebaldini, 2010
  - Lavalle, 2011

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

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

- lidar RH75 and RH100
- ignoring temporal decorrelation causes large bias and uncertainty
Temporal decorrelation model
Temporal decorrelation model

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

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

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

\[
\Delta \sigma^2 = \sigma_v^2 - \sigma_g^2
\]

Temporal decorrelation model

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

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

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

\[ \gamma_{t,g,v} = \frac{\mu \gamma_{tg} + \gamma_{tv}}{\mu + 1} \]

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

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

Validation of temporal decorrelation model

lidar canopy height (LVIS)

radar coherence (UAVSAR)

validation of dependence of temporal decorrelation on canopy height

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

Temporal decorrelation model

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

ground-to-volume scattering ratio

new property n. 2

temporal decorrelation is sensitive to wave polarization

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Validation of temporal decorrelation model

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

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

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

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

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

Method for canopy height estimation

- Single-baseline, repeat-pass 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
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

- lidar RH75 and RH100
- radar, new method (RMoG model) reduced bias and uncertainty
- radar, old method (RVoG model) large bias and uncertainty
Estimation of temporal parameters

Effects of the wind on 2-day interval UAVSAR data

Dynamic motion of scattering elements at ground

Dynamic motion of scattering elements in the canopy
Comparison UAVSAR time series and weather data

Coherence, precipitation and wind data in Harvard Forest, MA

effects of the rain
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