Forest Structure Characterization using UAVSAR PolInSAR and Tomography

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Basic Principles

Polarimetry
- Physics: dielectric and geometric properties

Interferometry
- Elevation and coherence of scattering center
- Volumetric and temporal properties

Polarimetric Interferometry
- Separation of scattering centers via polarization diversity

Tomography
- 3D scene reconstruction

Polarimetric SAR Interferometry

\[ T_6 = \langle k k^\dagger \rangle = \begin{bmatrix} T_{11} & \Omega_{12} \\ \Omega_{12}^\dagger & T_{22} \end{bmatrix} \quad k = \begin{bmatrix} k_1 \\ k_2 \end{bmatrix}, \quad k_i = \begin{bmatrix} HH_i \\ HV_i \\ VV_i \end{bmatrix} \]

\[ k = \begin{bmatrix} k_1 \\ k_2 \end{bmatrix}, \quad \gamma_{12}(\omega) = \frac{\omega^\dagger \Omega_{12} \omega}{\sqrt{\omega^\dagger T_{11} \omega \omega^\dagger T_{22} \omega}} \]
PolInSAR Vegetation Model

- Multi-layer model: \( T = \sum T_i \)
- Possible layer separation due to:
  - vertical structure
  - temporal behavior
  - polarimetric characteristics
- Every medium can be characterized with \( i \to \infty \to \text{unpractical!} \)
- Simplest cases: single layer & 2-layer models.

Coherence Unitary Circle (CUC)
2-Layer PolInSAR Vegetation Model

**Assumptions:**
- Ground and volume components not correlated
- Polarimetric stationarity
- No refraction effects and no differential extinction
- Volume and ground components homogeneous

**Model:** Ground + Volume Layers

\[
\mathbf{T}_6 = \begin{bmatrix} \mathbf{T} & \mathbf{\Omega} \end{bmatrix} \begin{bmatrix} \mathbf{T} = \mathbf{T}_g + \mathbf{T}_v \\
\mathbf{\Omega} = \gamma_g \mathbf{T}_g + \gamma_v \mathbf{T}_v
\end{bmatrix}
\]

\[
= \mathbf{R}_g \otimes \mathbf{T}_g + \mathbf{R}_v \otimes \mathbf{T}_v \quad \text{with} \quad \mathbf{R}_{g/v} = \begin{bmatrix} 1 & \gamma_{g/v} \\
\gamma_{g/v}^* & 1 \end{bmatrix}
\]

\[
T_{g/v}: \text{ground and volume PolSAR cov matrices} \\
\gamma_{g/v}: \text{ground and volume InSAR coherences}
\]

**Interferometric coherence model**

\[
\gamma \approx \gamma_{sys} \gamma_{geom} \gamma_{z} \gamma_{temp}
\]

\[
\gamma_{z} = e^{i\phi_0} \int f_0(z)e^{ikz}dz, \quad f_0(z) = \frac{e^{2\sigma \cos \theta_0 z}}{\int e^{2\sigma \cos \theta_0 z'}dz'}
\]

Polarimetric Homogeneous Medium Model

Orientation Randomness

Circular normal distribution of orientation angles:

\[ p(\psi | \tilde{\psi}, \kappa_\psi) = \frac{e^{\kappa_\psi \cos(2(\psi - \tilde{\psi}))}}{\pi I_0(\kappa_\psi)} \]

\[ \tau = \frac{\int p(\psi - \tilde{\psi})d\psi}{\pi \max p(\psi)} = I_0(\kappa)e^{-\kappa} \]

\[ \tilde{\psi} : \text{main orientation}, \quad \kappa : \text{degree of concentration} \]

Scattering Anisotropy: Spheroidal Particles

General formulation:

\[ T = R_{T(2\tilde{\psi})} \begin{bmatrix} 1 & g_c \delta^* & 0 \\ g_c \delta & \frac{(1+g)}{2} |\delta|^2 & 0 \\ 0 & 0 & \frac{(1-g)}{2} |\delta|^2 \end{bmatrix} R_{T(2\tilde{\psi})}^T \]

\[ R_{T(2\tilde{\psi})} : \text{Rotation to main orientation} \]

\[ g = \frac{I_2(\kappa)}{I_0(\kappa)}, \quad g_c = \frac{I_1(\kappa)}{I_0(\kappa)}, \quad \tau = I_0(\kappa)e^{-\kappa} \]

* assumption: \( \delta \) and \( \tau \) uncorrelated.

Physical Aspect ratio:

\[ r \approx \frac{b}{a} \begin{cases} < 1 & \text{prolate particles} \\ = 1 & \text{spherical particles} \\ > 1 & \text{oblate particles}. \end{cases} \]

Polarizability Ratio:

\[ \alpha_r = \frac{\alpha_a}{\alpha_b} = \frac{r + \epsilon_r + 1}{r \epsilon_r + 2} \]

Particle Scattering Anisotropy

\[ \delta_s(\nu, \alpha_r) = \frac{\alpha_r - 1}{\alpha_r + 1 + 2 \cot^2 \nu} \]

Effective Scattering Anisotropy

\[ \delta = \int \int \delta_s(\nu, \alpha_r)p(\nu)p(\alpha_r) d\nu d\alpha_r \]

2-Layer PolInSAR Vegetation Model

Single baseline PolInSAR:

\[
T_6 = \begin{bmatrix} T & \Omega \\ \Omega^\dagger & T \end{bmatrix} \{ T = T_g + T_v \quad \Omega = \gamma_g T_g + \gamma_v T_v \}
\]

\[= R_g \otimes T_g + R_v \otimes T_v \]

with \( R_{g/v} = \begin{bmatrix} 1 & \gamma_{g/v} \\ \gamma_{g/v} & 1 \end{bmatrix} \)

Multi-baseline PolInSAR:

\[
T_{MB} = \begin{bmatrix} T & \Omega_{12} & \ldots & \Omega_{1n} \\ \Omega_{12}^\dagger & T & \ldots & \Omega_{1n}^\dagger \\ \vdots & \vdots & \ddots & \vdots \\ \Omega_{1n}^\dagger & \Omega_{2n}^\dagger & \ldots & T \end{bmatrix} \rightarrow \begin{cases} T = T_g + T_v \\ \Omega_{ij} = \gamma_{ij} T_g + \gamma_{ij} T_v \end{cases}
\]

\[= \gamma_{g/v} T_g + \gamma_{g/v} T_v \]

with \( \gamma_{g/v} = \frac{1}{\gamma_{g/v}} \)

Polarimetry

- Vertical structure
- Attenuation
- Temporal change
- Noise

Interferometry

- Forest structure, density, elevations

Ground

- Backscatter power from the ground \( P_g \)
- Scattering mechanism
- Randomness
- Understory quantification
- Orientation/terrain slopes
- Soil moisture & roughness

Volume

- Backscatter power from the volume \( P_v \)
- Scattering mechanism
- Orientation randomness
- Main orientation

Indirect trunk and large branches characteristics

Canopy layer characteristics

SAR Tomography

• SAR Interferometry and SAR Polarimetry:
  – Largely developed at JPL (15-25y ago)

• SAR Tomography:
  – Mainly in Europe (last 10-15y)
  – Initial demonstrations: 10 years ago using airborne (ESAR) and space-borne sensors (ERS-1/2)
  – Potentially high resolution
  – Independent of solar illumination
  – High coverage

• Tomography offers the capability to sense vertically distributed information, e.g., vegetation and ice structure or deformation signals.
  – Extension of 2d SAR imaging to 3d and 4d (space-time).
  – Formation of an additional synthetic aperture in elevation.
Interpreting Polarimetric SAR Tomography over forests:
- vertical distribution of backscattered energy in dependence of polarization

Experimental Results

Harvard Forest
JPL’s UAVSAR
L-band
13 tracks

Spatial baselines: 5m – 125m
Temporal separation: 30 min – 11 days
Experimental Results

JPL’s UAVSAR sensor – Harvard Forest dataset – L-band

PolInSAR Height Estimate

Experimental Results

JPL’s UAVSAR sensor – Harvard Forest dataset – L-band

Overlaying PolInSAR Estimate and Pol-Tomogram

Experimental Results

- **Krycklan Catchment**
- Northern Sweden Boreal forest
- BioSAR II campaign 2008
- ESA-DLR-FOI-SLU
- DLR’s E-SAR sensor

- ascending/descending paths
- 6 tracks, respectively
- L- and P-bands
- 2*27 forest plots

Experimental Results

- Diffuse scattering, random orientations, high entropy
- Partially randomly oriented, but with preferred direction
- Deterministic scattering, uniformly aligned, e.g. only surface, or only double bounce
Experimental Results

Scattering mechanism type: total

Scattering mechanism type: volume

Scattering mechanism type: ground

Double-bounce e.g. trunk-ground, branch-branch, branch-trunk

Dipole scattering, e.g. volume/branch particles

Isotropic scattering, e.g. surface scattering

Conclusion

• Potential of Polarimetric SAR Interferometry and SAR Tomography for
  – vertical forest structure characterization
  – vegetation and scattering type characterization

• Observations from data:
  – No definitive model which would work for all forests
  – Temporal decorrelation - potentially large error source
  – Strong baseline choice dependence
  – Multiple baselines improve the estimation (*requires accurate processing & calibration)
  – Performance depends on forest and tree species type
  – L-band: no ground for dense forests, slopes, insufficient double-bounce

• Challenges:
  – Data processing and calibration
  – Long baselines processing for improved height resolution
  – Error analysis
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Thank you for your attention!
PolInSAR Coherence Set Distributions

- Example scenario:
  - $hv=20m$, extinction=$0.3\text{dB/m}$, ground phase=$0\text{ degree}$
  - SNR: $[9\text{dB}, 15\text{dB}]$, Temporal Brownian motion: $24\text{h}$ with sdev=$2\text{mm/h}$

Thermal decorrelation effects:

Temporal decorrelation effects:

Brownian motion with sdev=$2\text{mm/h}$ over $0, 1, 2, 5, 10, 20 \text{ days}$

A-posteriori cohset PDF’s and Confidence regions for 49 and 100 looks:

Confidence levels: $68\%, 95.5\%, 99.7\%, 99.994\%$
Non-modeled Variability

• Example PolInSAR height estimation errors due to model simplification. Induced non-modeled coherence magnitude and phase offsets or variabilities, and the resulting height estimation errors, if not compensated.

• Model: simple RVoG

• Example scenario:
  \( h_v = 25 \text{m}, \) incidence angle = 45 degrees, \( k_z = 0.15, \) extinction=0dB.

| Error Source          | \( \Delta |\gamma| \)  | \( \Delta \text{ arg } \gamma \)  | \( \Delta h_v (|\gamma|) \)  | \( \Delta h_v (\text{arg } \gamma) \) |
|----------------------|-----------------|-----------------|-----------------|-----------------|
| \( \gamma_{\text{temp}} \) of 0.8 | -0.10            | 0°              | 3.12m           | 0m              |
| \( \sigma_{\gamma_{\text{temp}}} \) of 50% | ±0.05            | 0°              | ±1.58m          | 0m              |
| Min\((c_g)\) of 15%   | -0.10            | -20.3°          | 2.94m           | -4.72m          |
| Canopy 75%            | 0.19             | 13.4°           | -6.25m          | 3.12m           |
| Extinction 0.2dB/m    | 0.07             | 35.4°           | -2.16m          | 8.23m           |
| \( \sigma_\phi, \sigma_\gamma \) (# looks = 25) | ±0.10            | ±13.7°          | ±3.26m          | ±3.19m          |
| \( \sigma_\phi, \sigma_\gamma \) (# looks = 100) | ±0.05            | ±6.85°          | ±1.61m          | ±1.60m          |