A New Approach to Estimate Forest Parameters Using Dual-Baseline POL-InSAR Data

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Outlines

- Forest Model in DoA Techniques
- Decorrelation Effects
- Dual-baseline Solution
- Experiment Results
- Conclusions
Forest Model in DoA Techniques

- **Forest Characteristics**
  - Volume scatterers
  - Vertical structure
    - Canopy, trunk, ground
  - Complex scattering
    - Single, double, multiple scattering
    - Average results of all echoes

- **Scattering Mechanisms**
  - Volume scattering
  - Dihedral scattering
  - Direct ground scattering

Mechanisms are *separable*
Their contributions can be regarded as returns from equivalent *point-like scattering centers.*

Figure. Pottier E. Advanced Concepts in POLSAR POL-InSAR Image Analysis. 2006.
Forest Model in DoA Techniques

- **Forest Model**
  - SAR observation
    
    \[ \begin{align*}
    E &= \tilde{S} \tilde{\sigma} + n \\
    \tilde{S} &= \begin{bmatrix} s^1 & \ldots & s^d \end{bmatrix} \\
    \tilde{\sigma} &= \begin{bmatrix} \sigma^1 e^{-j\frac{4\pi}{\lambda} R^1} & \ldots & \sigma^d e^{-j\frac{4\pi}{\lambda} R^d} \end{bmatrix}^T
    \end{align*} \]

  - \(n\): Additive white Gaussian noise
  - \(d\): number of the independent scattering centers
  - \(\sigma^i\): scattering amplitude of \(i\)th scattering center
  - \(R^i\): slant range of \(i\)th scattering center

  - **POLSAR Observation**
    
    \[ \tilde{k} = \begin{bmatrix} E_{HH} \\ \sqrt{2} E_{HV} \\ E_{VV} \end{bmatrix} = S \tilde{\sigma} + \tilde{n} \]

Forest Model in DoA Techniques

- **Forest Model**
  - **POL-InSAR Observation**
    \[
    \vec{k}_1 = S_1 \vec{\sigma} + \vec{n}_1 \\
    \vec{k}_2 = S_2 \vec{\sigma} + \vec{n}_2 \\
    \vec{\sigma} = \begin{bmatrix} \sigma^1 e^{-j \frac{4\pi}{\lambda} R^1} & \cdots & \sigma^d e^{-j \frac{4\pi}{\lambda} R^d} \end{bmatrix}^T
    \]

- **DoA**
  Equivalent scattering centers are **stable**
  \[
  S_1 \approx S_2 \quad \sigma_i^1 \approx \sigma_i^2 \quad R_i^2 \approx R_i^1 + \Delta R^i \\
  \vec{k}_1 = S \vec{\sigma} + \vec{n}_1 \\
  \vec{k}_2 = S \Phi \vec{\sigma} + \vec{n}_2
  \]

Ref. Yamada H. Polarimetric SAR Interferometry for Forest canopy analysis by using the super-resolution method. 2001

**Interferometric information**
\[
\Phi = \begin{bmatrix}
  -j \frac{4\pi}{\lambda} R^1 & 0 \\
  e^{-j \frac{4\pi}{\lambda} \Delta R^1} & \ddots \\
  0 & \cdots & -j \frac{4\pi}{\lambda} R^d
\end{bmatrix}
\]
DoA Techniques

– Observations

\[
C_6 = \begin{bmatrix}
\langle k_1 k_1^H \rangle & \langle k_1 k_2^H \rangle \\
\langle k_2 k_1^H \rangle & \langle k_2 k_2^H \rangle 
\end{bmatrix} = \begin{bmatrix}
C_{11} & C_{12} \\
C_{21} & C_{22}
\end{bmatrix}
\begin{bmatrix}
S \\
S\Phi
\end{bmatrix}
\begin{bmatrix}
\sigma^H \\
\sigma^H
\end{bmatrix}
\begin{bmatrix}
S^H & \Phi^H S^H \\
\end{bmatrix}
+ \sigma_n^2 E_n E_n^H
\]

– Estimate signal subspaces
– Calculate interferometric phases
– Inverse forest height
Forest Model in DoA Techniques

- **DoA Techniques**
  - **MUSIC / CAPON**
    - Signals are orthogonal to noises (large SNR)
    - Search for peak spectrum defined as
      \[
P(\phi) = \frac{\tilde{a}_s^H(\phi) \cdot \tilde{a}_s(\phi)}{\left| \tilde{a}_s^H(\phi) \cdot R \cdot \tilde{a}_s(\phi)^H \right|^2} \]
      \[
      \tilde{a}_s(\phi)^H = \begin{bmatrix} s_{HH}^i & \sqrt{2}s_{HV}^i & s_{VV}^i & e^{j\phi} s_{HH}^i & e^{j\phi} \sqrt{2}s_{HV}^i & e^{j\phi} s_{VV}^i \end{bmatrix}^T
      \]
      \[
      e^{j\phi} = e^{\frac{4\pi}{\lambda} \Delta R^d} , \text{ conjugate, } H \text{ conjugate and transpose}
      \]
    - CAPON ( \( R = C_6^{-1} \) ) ; MUSIC( \( R = E_n E_n^H \) )
    - Interferometric phases
      \[
      e^{-\frac{4\pi}{\lambda} \Delta R^i} = e^{-j\phi^i}, ..., e^{-\frac{4\pi}{\lambda} \Delta R^d} = e^{-j\phi^d}
      \]

Ref. Kasilingam D. A Technique for Removing Vegetation Bias from Polarimetric SAR Interferometry.
DoA Techniques

- ESPRIT Algorithm (SB ESPRIT)
  - Eigen decomposition
    \[ C_o = [\tilde{e}_1 \ldots \tilde{e}_d \ldots \tilde{e}_6] \Lambda_o [\tilde{e}_1 \ldots \tilde{e}_d \ldots \tilde{e}_6]^H \]
    \[ \lambda_1 > \ldots > \lambda_d \approx \lambda_{d+1} \approx \ldots \approx \lambda_6 \]
  - Signal subspaces
    \[ \begin{bmatrix} E_x^H \\ E_y^H \end{bmatrix} = \begin{bmatrix} \sqrt{\lambda_1 \tilde{e}_1} & \ldots & \sqrt{\lambda_d \tilde{e}_d} \end{bmatrix} = \begin{bmatrix} ST \\ S \Phi T \end{bmatrix} \]
  - Eigen vectors
    \[ \begin{bmatrix} E_x^H \\ E_y^H \end{bmatrix} \begin{bmatrix} E_x & E_y \end{bmatrix} = \begin{bmatrix} E_{11} & E_{12} \\ E_{21} & E_{22} \end{bmatrix} \Lambda' \begin{bmatrix} E_{11} & E_{12} \\ E_{21} & E_{22} \end{bmatrix} \]
    \[ \lambda_1' > \ldots > \lambda_d' > \lambda_{d+1}' > \ldots > \lambda_{2d}' \]
  - Results
    \[ T^H \Phi T = -E_{12}E_{22}^{-1} = E_d \Lambda_d E_d^H \]
    \[ e^{-\frac{4\pi}{\lambda} \Delta R^i} = e^{-j\phi} \frac{\lambda_1}{|\lambda_1|}, \ldots, e^{-\frac{4\pi}{\lambda} \Delta R^d} = e^{-j\phi}' \frac{\lambda_d}{|\lambda_d|} \]

Ref. Guillaso S. Evaluation of the ESPRIT approach in polarimetric interferometric SAR.
DoA Techniques
- Phase Difference between Ground and Canopy
  - Single Stable Scattering Center
    \[ \Delta \phi = 0 \]
  - Two Stable Scattering Center
    - Errors Caused by Phase unwrapping
    \[ \Delta \phi = \text{Max} \left\{ |\phi^1 - \phi^2| \right\} \]
  - Three Stable Scattering Center
    - Phase difference between ground and canopy is the largest
    - Errors Caused by Phase Unwrapping
    \[ \Delta \phi = \max \left\{ |\phi^m - \phi^k| \right\} \quad m, k = 1, ..., d \]

Forest Height Estimation
\[ h_v = \frac{\Delta \phi}{|\kappa_z|} \]
Decorrelation in Forest

Problems

- Model Applicability
  - good for equivalent scattering center in canopy?

  assumption for stable scattering center in forest
  - inaccurate interferometric information

  volume scattering is strong but its coherence is low

- Interferometric Phases
  - hard to identify canopy and ground information

  errors caused by phase unwrapping
Outline

- Forest Model in DoA Techniques
- Decorrelation Effects
- Dual-baseline Solution
- Experiment Results
- Conclusions
Dual-baseline solution

- Our aim
  - **Improve forest height estimations**
    - solve phase wrapping
  - **Estimate the stable scattering centers**
    - Separate the stable SM and the unstable SM: coherence
    - Only use the SM with high coherence
    - suffer less from temporal and volume decorrelation
    - provide interferometric information of high quality

- Dual-Baseline Data
  - Long Time interval
    - changes of forest scatterers
    - temporal decorrelation
  - Additional Baseline
    - distribution of scatterers
    - volume decorrelation
  - More interferometric phases
    - estimate phase error
    - provide accurate phase difference
Dual-baseline solution

- **Proposed Approach**
  - Stable scattering centers always keep high coherences
    \[ |\gamma_{pq}(\tilde{\omega})| = \frac{\tilde{\omega}C_{pq}\tilde{\omega}}{\sqrt{\tilde{\omega}C_{pp}\tilde{\omega} \cdot \tilde{\omega}C_{qq}\tilde{\omega}}} \]
  - **DB Coherence Optimization**
    - optimization criteria
      \[ \sum_{p \neq q} |\gamma_{pq}(\tilde{\omega})| = \sum_{p \neq q} \frac{|\tilde{\omega}C_{pq}\tilde{\omega}|}{\sqrt{\tilde{\omega}C_{pp}\tilde{\omega} \cdot \tilde{\omega}C_{qq}\tilde{\omega}}} \]
    - iterative estimation for optimal vector (Maxim)
      \[ H\tilde{\omega}_{opt}^m = \lambda C_e \tilde{\omega}_{opt}^m \]
      \[ H = \sum_{p \neq q} C_{pq} e^{-j\phi_{pq}}, C_e = \frac{1}{N} \sum_{p=1}^{N} C_{pp} \]
      \[ \phi_{pq} = \text{arg} \left( \tilde{\omega}_{opt}^m H C_{pq} \tilde{\omega}_{opt}^m \right), \quad |\tilde{\omega}_{opt}^m H \tilde{\omega}_{opt}^k| = 0 \]
  - Signal components are separated according to coherences
    \[ C_{pq} = \gamma_{pq}^1 \sigma_{pq}^1 \sigma_{pq}^1 \tilde{\omega}_{opt}^1 H + \gamma_{pq}^2 \sigma_{pq}^2 \sigma_{pq}^2 \tilde{\omega}_{opt}^2 H + \gamma_{pq}^3 \sigma_{pq}^3 \sigma_{pq}^3 \tilde{\omega}_{opt}^3 H \]
    - If there is coherence \[ |\gamma_{12}(\tilde{\omega}_{opt}^m)|, |\gamma_{13}(\tilde{\omega}_{opt}^m)|, \text{ or } |\gamma_{23}(\tilde{\omega}_{opt}^m)| \] lower than 0.5, the \( m^{th} \) scattering center is not stable.
    - The number of stable scattering centers is \( d \).
Dual-baseline solution

- **Dual-Baseline ESPRIT Algorithm (DB ESPRIT)**
  - Eigen decomposition
    \[
    C_9 = \begin{bmatrix}
    C_{11} & C_{12} & C_{13} \\
    C_{21} & C_{22} & C_{23} \\
    C_{31} & C_{32} & C_{33}
    \end{bmatrix} = \begin{bmatrix}
    \bar{e}_1 & \cdots & \bar{e}_d & \cdots & \bar{e}_9
    \end{bmatrix} \Lambda_y \begin{bmatrix}
    \bar{e}_1 & \cdots & \bar{e}_d & \cdots & \bar{e}_9
    \end{bmatrix}^H
    \]
  - Signal subspaces
    \[
    \begin{bmatrix}
    E_X \\
    E_Y \\
    E_Z
    \end{bmatrix} = \begin{bmatrix}
    \sqrt{\lambda_1} \bar{e}_1 & \cdots & \sqrt{\lambda_d} \bar{e}_d
    \end{bmatrix} = \begin{bmatrix}
    ST \\
    S \Phi_{12} T \\
    S \Phi_{13} T
    \end{bmatrix}
    \]
  - Eigen vectors
    \[
    \begin{bmatrix}
    E_X^H \\
    E_Y^H \\
    E_Z^H
    \end{bmatrix} = \begin{bmatrix}
    E_X & E_Y & E_Z
    \end{bmatrix} = E \Lambda_{3d} E
    \]
  - Obtain sub matrices
    \[
    E = \begin{bmatrix}
    E_{11} & E_{12} & E_{13} \\
    E_{21} & E_{22} & E_{23} \\
    E_{31} & E_{32} & E_{33}
    \end{bmatrix}
    \text{ satisfying } \begin{bmatrix}
    E_X E_{12} + E_Y E_{22} + E_Z E_{32} = 0 \\
    E_X E_{13} + E_Y E_{23} + E_Z E_{33} = 0
    \end{bmatrix}
    \]
  - Estimate interferometric phases
    \[
    \phi_{12}^m = \arg \left( \lambda_{12}^m \right) \text{ from } \begin{bmatrix}
    T^{-1} \Phi_{12} T = \begin{bmatrix}
    E_{12} E_{32}^{-1} - E_{13} E_{33}^{-1}
    \end{bmatrix}
    \end{bmatrix} = \begin{bmatrix}
    E_{d12} \Lambda_{d12} E_{d12}^H
    \end{bmatrix}
    \]
    \[
    \phi_{13}^m = \arg \left( \lambda_{13}^m \right) \text{ from } \begin{bmatrix}
    T^{-1} \Phi_{13} T = \begin{bmatrix}
    E_{12} E_{22}^{-1} - E_{13} E_{23}^{-1}
    \end{bmatrix}
    \end{bmatrix} = \begin{bmatrix}
    E_{d13} \Lambda_{d13} E_{d13}^H
    \end{bmatrix}
    \]
Dual-baseline solution

- Proposed Approach
  - Interferometric Phases
    - Suppress volume and temporal decorrelation
    
    \[
    \left\{ \gamma_{12}^1, \gamma_{13}^1, \gamma_{23}^1 \right\} \cdots \left\{ \gamma_{12}^d, \gamma_{13}^d, \gamma_{23}^d \right\}
    \]

    - Obtain the interferometric Phases of High Quality

    \[
    \phi_{12}^1 = \arg(\gamma_{12}^1), \quad \phi_{13}^1 = \arg(\gamma_{13}^1), \quad \phi_{23}^1 = \arg(\gamma_{23}^1)
    \]

    \[\cdots\]

    \[
    \phi_{12}^d = \arg(\gamma_{12}^d), \quad \phi_{13}^d = \arg(\gamma_{13}^d), \quad \phi_{23}^d = \arg(\gamma_{23}^d)
    \]
Dual-baseline solution

Phase Estimation

- Direct Phase Estimation
  - problems:
    - unwrapping
    - three unknowns
    - two equations

∃ integral number \( m_{12}, m_{13} \) satisfying

\[
\begin{align*}
-\kappa_{z12} h^m &= -\phi_{12}^m + 2m_{12}\pi \\
-\kappa_{z13} h^m &= -\phi_{13}^m + 2m_{13}\pi
\end{align*}
\]
Dual-baseline solution

- Phase Estimation
  - Estimate Interferometric Phase Difference
    - Phase difference would not exceed the range \((-2\pi, 2\pi]\)
    - Select Phase Combination

\[
\{\Delta \phi_{12}^{mk}, \Delta \phi_{13}^{mk}\} = \begin{cases} 
\{\phi_{12}^m - \phi_{12}^k, \phi_{13}^m - \phi_{13}^k\} \\
2\pi - \phi_{12}^m - \phi_{12}^k, \phi_{13}^m - \phi_{13}^k \\
\phi_{12}^m - \phi_{12}^k, 2\pi - \phi_{13}^m - \phi_{13}^k \\
2\pi - \phi_{12}^m - \phi_{12}^k, 2\pi - \phi_{13}^m - \phi_{13}^k
\end{cases}
\]

according to

\[
\left(\left|k_{z12}\right| - \left|k_{z13}\right|\right)\left(\left|\Delta \phi_{12}^{mk}\right| - \left|\Delta \phi_{13}^{mk}\right|\right) \geq 0
\]

and

\[
\operatorname{Min} \left|\Delta \phi_{12}^{mk}\right|\left|k_{z13}\right| - \left|\Delta \phi_{13}^{mk}\right|\left|k_{z12}\right|
\]

since

\[
\Delta h^{mk} = \frac{|\Delta \phi_{12}^{mk}|}{|k_{z12}|} = \frac{|\Delta \phi_{13}^{mk}|}{|k_{z13}|}
\]
Dual-baseline solution

- height difference estimation using least square method

\[
\Delta h_{est}^{mk} = \text{Min} \left( \left[ \kappa_{z12} \left| \Delta h^{mk} - |\Delta \phi_{12}^{mk}| \right| \right]^2 + \left[ \kappa_{z13} \left| \Delta h^{mk} - |\Delta \phi_{13}^{mk}| \right| \right]^2 \right)
\]

\[
\Rightarrow h_v = \text{Max} \left( \left| \Delta h_{est}^{mk} \right| \right)
\]

Height difference between ground and canopy is the largest.

Outline

- Forest Model in DoA Techniques
- Decorrelation Effects
- Dual-baseline Solution
- Experiment Results
- Conclusions
L band ESAR Data
- Truanstein, Germany (2003)
- 4650 × 1414 pixel
- Master Data
- Slave-1 Data (B12)
  - $B_h = -4.3503m$
  - $B_v = 0.067m$
  - 20 minutes interval
- Slave-2 Data (B13)
  - $B_h = -10.130m$
  - $B_v = 0.307$
  - 10 minutes interval

Test Site
- Eight Forest Areas
- Known Forest Heights
Experiment Design

- **SB ESPRIT (B13) vs DB ESPRIT (B12-B13)**
  - DB ESPRIT
    - Centers’ number estimated from Coherence optimization
    - separate signal subspaces
    - estimate forest height
  - analyze the improvement brought by additional baseline

- **DB ESPRIT vs Proposed Approach**
  - DB ESPRIT
    - Centers’ number estimated from Coherence optimization
    - separate signal subspaces
    - interferometric phase for dual-baseline
    - calculate height differences and forest height
  - Proposed Approach
    - Centers’ number estimated from Coherence optimization
    - interferometric phase for dual-baseline
    - calculate height differences and forest height
  - discuss the influence of decorrelations

- **SB ESPRIT**
  - discuss errors caused by phase unwrapping
EXPERIMENTAL RESULTS

- Forest Height
  - SB ESPRIT
    - overestimation
  - DB ESPRIT
    - Under estimation
  - Proposed Approach
    - Closest estimation

Diagram showing comparisons of forest height estimations in Profile 1 and Profile 2 with reference height.
EXPERIMENTAL RESULTS

Average Forest Height

- SB ESPRIT
  - Large overestimation
- DB ESPRIT
  - Closer estimation
- Proposed Approach
  - Closest Estimation
  - Effective to handle phase unwrapping and phase error

<table>
<thead>
<tr>
<th>Test Areas</th>
<th>SB ESPRIT</th>
<th>DB ESPRIT</th>
<th>Proposed Approach</th>
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<td>Average Height</td>
<td>Average Height</td>
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<td>13.24</td>
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<tr>
<td>T8</td>
<td>18.66</td>
<td>35.87</td>
<td>17.90</td>
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</table>
EXPERIMENTAL RESULTS

- Deviation from Reference Height
  - **DB ESPRIT**
    - Large deviation
  - **Proposed Approach**
    - Smaller deviation

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Forest Model in DoA Techniques

- **DoA Techniques**
  - Phase Difference between Ground and Canopy
    - Single Stable Scattering Center
      \[ \Delta \phi = 0 \]
    - Two Stable Scattering Center
      - Errors Caused by Phase unwrapping
      \[ \Delta \phi = \text{Max} \left\{ \left| \phi^1 - \phi^2 \right|, 2\pi - \left| \phi^1 - \phi^2 \right| \right\} \]
    - Three Stable Scattering Center
      - Phase difference between ground and canopy is the largest
      - Errors Caused by Phase Unwrapping
      \[ \Delta \phi = \max \left\{ \left| \phi^m - \phi^k \right|, 2\pi - \left| \phi^m - \phi^k \right| \right\} \quad m, k = 1, \ldots, d \]
  - Forest Height Estimation
    \[ h_v = \frac{\Delta \phi}{|\kappa_z|} \]
EXPERIMENTAL RESULTS

SB ESPRIT

- Considering Phase Unwrapping (1)
  \[ \Delta \phi = \max \left\{ |\phi^m - \phi^k|, 2\pi - |\phi^m - \phi^k| \right\} \]
  \[ m, k = 1, \ldots, d \]

- Neglect Phase Unwrapping (2)
  \[ \Delta \phi = \max \left\{ |\phi^m - \phi^k| \right\} \]
  \[ m, k = 1, \ldots, d \]

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Conclusions-1

- **Dual-baseline data**
  - Additional observation
    - detect the change of scattering center
      - the interferometric phase differences between different baselines
    - provide additional information for stable scattering center
      - Use the phase differences to improve height estimate
      - (SB ESPRIT vs DB ESPRIT)
  - Estimate scattering centers’ number
    - keep high coherence all the time

- **Proposed Approach**
  - Coherence Optimization
    - Suppress volume and temporal decorrelation
    - Improve the quality of interferometric phases
  - Height difference Estimation
    - Handle the phase unwrapping
    - Provide accurate phase estimations
Jan 26-30, 2009  Frascati, Italy

Thank You!

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