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

Lu Bai, Wen Hong, Fang Cao, Yongsheng Zhou

bailu81@gmail.com
fcao@mail.ie.ac.cn

National Key Laboratory of Microwave Imaging Technology

Institute of Electronics, Chinese Academy of Sciences

Outlines

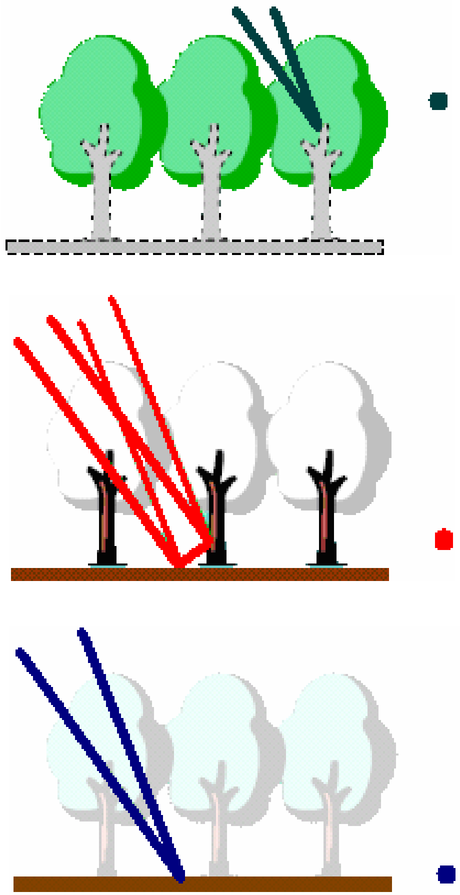
- **Forest Model in DoA Techniques**
- **Decorrelation Effects**
- **Dual-baseline Solution**
- **Experiment Results**
- **Conclusions**

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*.



Ref. Cloude S.R., Papathanassiou K.P. Polarimetric SAR Interferometry. 1998.
Figure. Pottier E. Advanced Concepts in POLSAR POL-InSAR Image Analysis. 2006.

Forest Model in DoA Techniques

- Forest Model
  - SAR observation

$$E = \vec{s}\vec{\sigma} + n$$

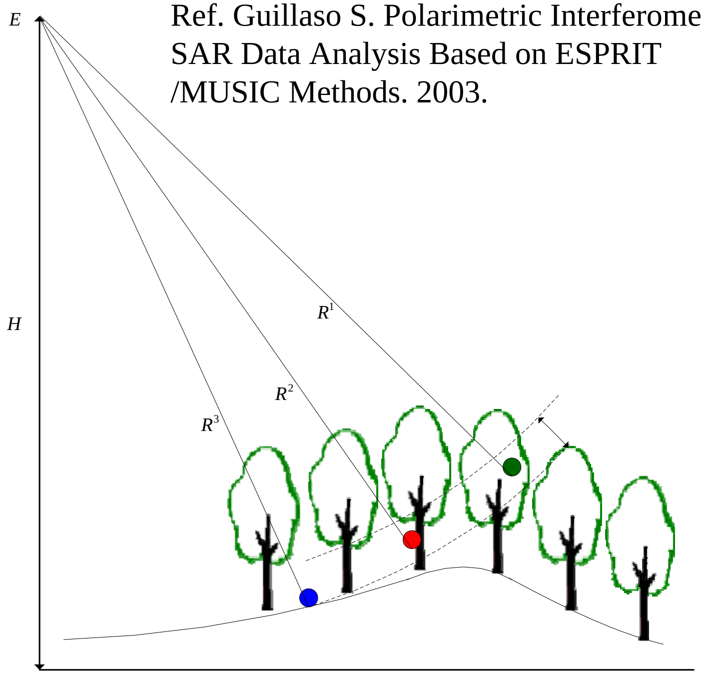
$$\vec{s} = \begin{bmatrix} s^1 & \cdots & s^d \end{bmatrix} \quad \vec{\sigma} = \begin{bmatrix} \sigma^1 e^{-j\frac{4\pi}{\lambda}R^1} & \cdots & \sigma^d e^{-j\frac{4\pi}{\lambda}R^d} \end{bmatrix}^T$$

n: Addictive white Gaussian noise

d: number of the independent scattering centers

σ^i : scattering amplitude of ith scattering center

R^i : slant range of ith scattering center



Ref. Guillaso S. Polarimetric Interferometric SAR Data Analysis Based on ESPRIT /MUSIC Methods. 2003.

  - POLSAR Observation

$$\vec{k} = \begin{bmatrix} E_{HH} \\ \sqrt{2}E_{HV} \\ E_{VV} \end{bmatrix} = \mathbf{S}\vec{\sigma} + \vec{n}$$

Polarimetric information

$$\mathbf{S} = \begin{bmatrix} s_{HH}^1 & \cdots & s_{HH}^d \\ \sqrt{2}s_{HV}^1 & \cdots & \sqrt{2}s_{HV}^d \\ s_{VV}^1 & \cdots & s_{VV}^d \end{bmatrix}$$

HH, HV, VV : 3 dimensions $d \le 3$

At most 3 independent scattering mechanisms

Forest Model in DoA Techniques

- Forest Model
  - POL-InSAR Observation

$$\vec{k}_1 = \mathbf{S}_1 \vec{\sigma}_1 + \vec{n}_1$$

$$\vec{k}_2 = \mathbf{S}_2 \vec{\sigma}_2 + \vec{n}_2$$

$$\vec{\sigma} = \begin{bmatrix} \sigma^1 e^{-j\frac{4\pi}{\lambda}R^1} & \cdots & \sigma^d e^{-j\frac{4\pi}{\lambda}R^d} \end{bmatrix}^T$$

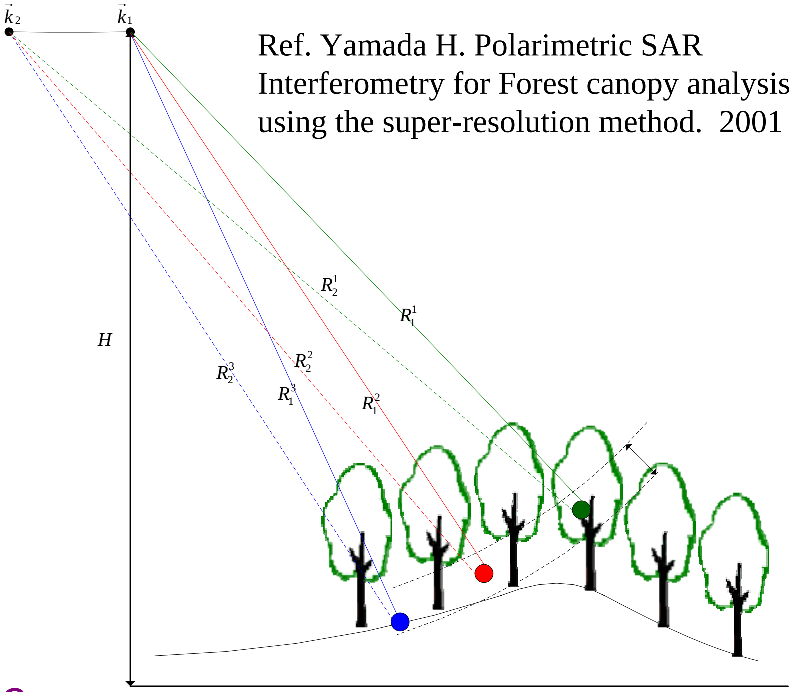
  - DoA

Equivalent scattering centers are stable

$$\mathbf{S}_1 \approx \mathbf{S}_2 \qquad \sigma_1^i \approx \sigma_2^i \qquad R_2^i \approx R_1^i + \Delta R^i$$

$$\vec{k}_1 = \mathbf{S} \vec{\sigma} + \vec{n}_1$$

$$\vec{k}_2 = \mathbf{S} \Phi \vec{\sigma} + \vec{n}_2$$



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

Interferometric information

$$\Phi = \begin{bmatrix} e^{-j\frac{4\pi}{\lambda}\Delta R^1} & & 0 \\ & \ddots & \\ 0 & & e^{-j\frac{4\pi}{\lambda}\Delta R^d} \end{bmatrix}$$

Forest Model in DoA Techniques

- DoA Techniques
  - Observations

$$\mathbf{C}_6=\begin{bmatrix}\left\langle \vec{k}_1\vec{k}_1^{\,H}\right\rangle & \left\langle \vec{k}_1\vec{k}_2^{\,H}\right\rangle\\ \left\langle \vec{k}_2\vec{k}_1^{\,H}\right\rangle & \left\langle \vec{k}_2\vec{k}_2^{\,H}\right\rangle\end{bmatrix}=\begin{bmatrix}\mathbf{C}_{11} & \mathbf{C}_{12}\\ \mathbf{C}_{21} & \mathbf{C}_{22}\end{bmatrix}=\begin{bmatrix}\mathbf{S}\\ \mathbf{S\Phi}\end{bmatrix}\left\langle \vec{\sigma}\vec{\sigma}^{H}\right\rangle\begin{bmatrix}\mathbf{S}^H & \mathbf{\Phi}^H\mathbf{S}^H\end{bmatrix}+\sigma_n^2\mathbf{E}_n\mathbf{E}_n^{\,H}$$

  - 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

$$P(\phi)=\frac{\vec{a}_{\vec{s}}(\phi)^{H}\cdot\vec{a}_{\vec{s}}(\phi)}{\left|\vec{a}_{\vec{s}}(\phi)^{H}\cdot\mathbf{R}\cdot\vec{a}_{\vec{s}}(\phi)^{H}\right|^{2}}$$

$$\vec{a}_{\vec{s}}(\phi)^{H}=\left[s_{HH}^{i\ *}\quad\sqrt{2}s_{HV}^{i\ *}\quad s_{VV}^{i\ *}\quad e^{j\phi^{i}}s_{HH}^{i\ *}\quad e^{j\phi^{i}}\sqrt{2}s_{HV}^{i\ *}\quad e^{j\phi^{i}}s_{VV}^{i\ *}\right]$$

$$e^{j\phi^{i}}=e^{j\frac{4\pi}{\lambda}\Delta R^{i}},\ ^{*}\ \ conjugate,\ ^{H}\ \ conjugate\ \ and\ \ transpose$$

- CAPON ($\mathbf{R}=\mathbf{C}_6^{-1}$) ; MUSIC($\mathbf{R}=\mathbf{E}_n\mathbf{E}_n^{H}$)
- Interferometric phases

$$e^{-j\frac{4\pi}{\lambda}\Delta R^{1}}=e^{-j\phi^{1}},\ldots,e^{-j\frac{4\pi}{\lambda}\Delta R^{d}}=e^{-j\phi^{d}}$$

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

Forest Model in DoA Techniques

- DoA Techniques
  - ESPRIT Algorithm (SB ESPRIT)
    - Eigen decomposition

$$\mathbf{C}_6 = [\vec{e}_1 \quad \ldots \quad \vec{e}_d \quad \ldots \quad \vec{e}_6]\mathbf{\Lambda}_6[\vec{e}_1 \quad \ldots \quad \vec{e}_d \quad \ldots \quad \vec{e}_6]^H \qquad \lambda_1 > \ldots > \lambda_d \gg \lambda_{d+1} \approx \ldots \approx \lambda_6$$

    - Signal subspaces

$$\begin{bmatrix} \mathbf{E}_X \\ \mathbf{E}_Y \end{bmatrix} = \left[\sqrt{\lambda_1}\vec{e}_1 \quad \ldots \quad \sqrt{\lambda_d}\vec{e}_d\right] = \begin{bmatrix} \mathbf{ST} \\ \mathbf{S\Phi T} \end{bmatrix}$$

    - Eigen vectors

$$\begin{bmatrix} \mathbf{E}_X{}^H \\ \mathbf{E}_Y{}^H \end{bmatrix}[\mathbf{E}_X \quad \mathbf{E}_Y] = \begin{bmatrix} \mathbf{E}_{11} & \mathbf{E}_{12} \\ \mathbf{E}_{21} & \mathbf{E}_{22} \end{bmatrix}\mathbf{\Lambda}'\begin{bmatrix} \mathbf{E}_{11} & \mathbf{E}_{12} \\ \mathbf{E}_{21} & \mathbf{E}_{22} \end{bmatrix}^H$$

$$\lambda_1' > \ldots > \lambda_d' > \lambda_{d+1}' > \ldots > \lambda_{2d}'$$

    - Results

$$\mathbf{T}^{-1}\mathbf{\Phi}\mathbf{T} = -\mathbf{E}_{12}\mathbf{E}_{22}{}^{-1} = \mathbf{E}_d\Lambda_d\mathbf{E}_d{}^H$$

$$e^{-j\frac{4\pi}{\lambda}\Delta R^1} = e^{-j\phi^1} = \frac{\lambda_1}{|\lambda_1|}, \ldots, e^{-j\frac{4\pi}{\lambda}\Delta R^d} = e^{-j\phi^d} = \frac{\lambda_d}{|\lambda_d|}$$

Ref. Guillaso S. Evaluation of the ESPRIT approach in polarimetric interferometric SAR.

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

$$\Delta\phi = Max\left\{\left|\phi^1 - \phi^2\right|\right\}$$

    - Three Stable Scattering Center
      - Phase difference between ground and canopy is the largest
      - Errors Caused by Phase Unwrapping

$$\Delta\phi = \max\left\{\left|\phi^m - \phi^k\right|\right\} \qquad m,k = 1,\ldots,d$$

  - Forest Height Estimation

$$h_V = \frac{\Delta\phi}{\left|\kappa_z\right|}$$

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

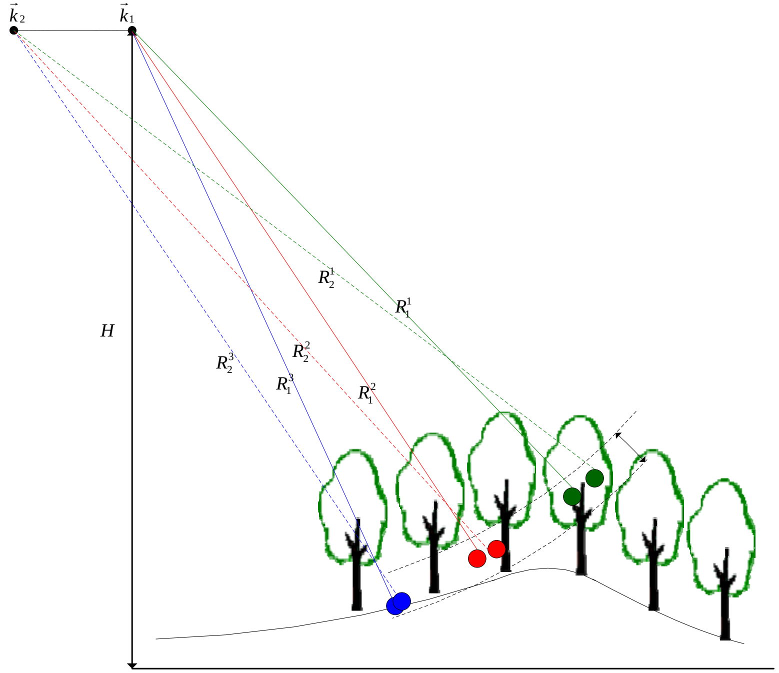
      errors caused by phase unwrapping

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

$$\left|\gamma_{pq}(\vec{\omega})\right| = \frac{\left|\vec{\omega}\mathbf{C}_{pq}\vec{\omega}\right|}{\sqrt{\vec{\omega}\mathbf{C}_{pp}\vec{\omega}\cdot\vec{\omega}\mathbf{C}_{qq}\vec{\omega}}}$$

Ref. Maxim N., Lauren F. Andreas R.
Polarimetric Coherence Optimization
for Multibaseline SAR Data. 2007.

- DB Coherence Optimization
  - optimization criteria $\sum_{p\neq q}\left|\gamma_{pq}(\vec{\omega})\right| = \sum_{p\neq q}\frac{\left|\vec{\omega}\mathbf{C}_{pq}\vec{\omega}\right|}{\sqrt{\left|\vec{\omega}\mathbf{C}_{pq}\vec{\omega}\right|\cdot\left|\vec{\omega}\mathbf{C}_{pq}\vec{\omega}\right|}}$
  - iterative estimation for optimal vector (Maxim)

$$\mathbf{H}\vec{\omega}_{opt}^{m} = \lambda\mathbf{C}_{e}\vec{\omega}_{opt}^{m} \qquad \mathbf{H}=\sum_{p\neq q}\mathbf{C}_{pq}e^{-j\phi_{pq}},\mathbf{C}_{e} = \frac{1}{N}\sum_{p=1}^{N}\mathbf{C}_{pp}$$

$$\phi_{pq} = arg\left(\vec{\omega}_{opt}^{m\ H}\mathbf{C}_{pq}\vec{\omega}_{opt}^{m}\right) \qquad \left|\vec{\omega}_{opt}^{m\ H}\vec{\omega}_{opt}^{k}\right| = 0$$

Estimate number of Scattering Centers

- Signal components are separated according to coherences

$$\mathbf{C}_{pq} = \gamma_{pq}^{1}\sigma_{p}^{1}\sigma_{q}^{1}\vec{\omega}_{opt}^{1}\vec{\omega}_{opt}^{1\ H} + \gamma_{pq}^{2}\sigma_{p}^{2}\sigma_{q}^{2}\vec{\omega}_{opt}^{2}\vec{\omega}_{opt}^{2\ H} + \gamma_{pq}^{3}\sigma_{p}^{3}\sigma_{q}^{3}\vec{\omega}_{opt}^{3}\vec{\omega}_{opt}^{3\ H} \quad \left(\sigma_{p}^{m} = \sqrt{\vec{\omega}_{opt}^{m\ H}\mathbf{C}_{pp}\vec{\omega}_{opt}^{m}}\right)$$

  - If there is coherence $\left|\gamma_{12}\left(\vec{\omega}_{opt}^{m}\right)\right|$, $\left|\gamma_{13}\left(\vec{\omega}_{opt}^{m}\right)\right|$, or $\left|\gamma_{23}\left(\vec{\omega}_{opt}^{m}\right)\right|$ lower than 0.5, the mth scattering center is not stable.
  - The number of stable scattering centers is d.

Dual-baseline solution

Dual-Baseline ESPRIT Algorithm (DB ESPRIT)

- Eigen decomposition

$$\mathbf{C}_9 = \begin{bmatrix} \mathbf{C}_{11} & \mathbf{C}_{12} & \mathbf{C}_{13} \\ \mathbf{C}_{21} & \mathbf{C}_{22} & \mathbf{C}_{23} \\ \mathbf{C}_{31} & \mathbf{C}_{32} & \mathbf{C}_{33} \end{bmatrix}$$

$$= \begin{bmatrix} \vec{e}_1 & \dots & \vec{e}_d & \dots & \vec{e}_9 \end{bmatrix} \mathbf{\Lambda}_9 \begin{bmatrix} \vec{e}_1 & \dots & \vec{e}_d & \dots & \vec{e}_9 \end{bmatrix}^H$$

- Signal subspaces

$$\begin{bmatrix} \mathbf{E}_X \\ \mathbf{E}_Y \\ \mathbf{E}_Z \end{bmatrix} = \begin{bmatrix} \sqrt{\lambda_1}\vec{e}_1 & \dots & \sqrt{\lambda_d}\vec{e}_d \end{bmatrix} = \begin{bmatrix} \mathbf{ST} \\ \mathbf{S\Phi}_{12}\mathbf{T} \\ \mathbf{S\Phi}_{13}\mathbf{T} \end{bmatrix}$$

- Eigen vectors

$$\begin{bmatrix} \mathbf{E}_X{}^H \\ \mathbf{E}_Y{}^H \\ \mathbf{E}_Z{}^H \end{bmatrix} \begin{bmatrix} \mathbf{E}_X & \mathbf{E}_Y & \mathbf{E}_Z \end{bmatrix} = \mathbf{E\Lambda}_{3d}\mathbf{E}$$

- Obtain sub matrices $\mathbf{E} = \begin{bmatrix} \mathbf{E}_{11} & \mathbf{E}_{12} & \mathbf{E}_{13} \\ \mathbf{E}_{21} & \mathbf{E}_{22} & \mathbf{E}_{23} \\ \mathbf{E}_{31} & \mathbf{E}_{32} & \mathbf{E}_{33} \end{bmatrix}$ satisfying

$$\mathbf{E}_X\mathbf{E}_{12} + \mathbf{E}_Y\mathbf{E}_{22} + \mathbf{E}_Z\mathbf{E}_{32} = \mathbf{0}$$
$$\mathbf{E}_X\mathbf{E}_{13} + \mathbf{E}_Y\mathbf{E}_{23} + \mathbf{E}_Z\mathbf{E}_{33} = \mathbf{0}$$

- Estimate interferometic phases

$$\phi_{12}^m = arg\left(\lambda_{12}^m\right)$$
$$\phi_{13}^m = arg\left(\lambda_{13}^m\right)$$

from

$$\mathbf{T}^{-1}\mathbf{\Phi}_{12}\mathbf{T} = \left(\mathbf{E}_{12}\mathbf{E}_{32}{}^{-1} - \mathbf{E}_{13}\mathbf{E}_{33}{}^{-1}\right)\left(\mathbf{E}_{23}\mathbf{E}_{33}{}^{-1} - \mathbf{E}_{22}\mathbf{E}_{32}{}^{-1}\right)^{-1} = \mathbf{E}_{d12}\Lambda_{d12}\mathbf{E}_{d12}{}^H$$

$$\mathbf{T}^{-1}\mathbf{\Phi}_{13}\mathbf{T} = \left(\mathbf{E}_{12}\mathbf{E}_{22}{}^{-1} - \mathbf{E}_{13}\mathbf{E}_{23}{}^{-1}\right)\left(\mathbf{E}_{33}\mathbf{E}_{23}{}^{-1} - \mathbf{E}_{32}\mathbf{E}_{22}{}^{-1}\right)^{-1} = \mathbf{E}_{d13}\Lambda_{d13}\mathbf{E}_{d13}{}^H$$

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

$$\begin{array}{l}
\phi_{12}^{1}=\arg\left(\gamma_{12}^{1}\right),\phi_{13}^{1}=\arg\left(\gamma_{13}^{1}\right),\phi_{23}^{1}=\arg\left(\gamma_{23}^{1}\right)\\
\cdots\\
\phi_{12}^{d}=\arg\left(\gamma_{12}^{d}\right),\phi_{13}^{d}=\arg\left(\gamma_{13}^{d}\right),\phi_{23}^{d}=\arg\left(\gamma_{23}^{d}\right)
\end{array}$$

Dual-baseline solution

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

Phase Unwrapping

э intergral number m_{12}, m_{13} *satisfying*

$$\begin{cases} -\kappa_{z12} h^m = -\phi_{12}^m + 2m_{12}\pi \\ -\kappa_{z13} h^m = -\phi_{13}^m + 2m_{13}\pi \end{cases}$$

Dual-baseline solution

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

$$\left\{\left|\Delta\phi_{12}{}^{mk}\right|, \left|\Delta\phi_{13}{}^{mk}\right|\right\} = \begin{cases} \left\{\left|\phi_{12}^{m} - \phi_{12}^{k}\right|, \left|\phi_{13}^{m} - \phi_{13}^{k}\right|\right\} \\ \left\{2\pi - \left|\phi_{12}^{m} - \phi_{12}^{k}\right|, \left|\phi_{13}^{m} - \phi_{13}^{k}\right|\right\} \\ \left\{\left|\phi_{12}^{m} - \phi_{12}^{k}\right|, 2\pi - \left|\phi_{13}^{m} - \phi_{13}^{k}\right|\right\} \\ \left\{2\pi - \left|\phi_{12}^{m} - \phi_{12}^{k}\right|, 2\pi - \left|\phi_{13}^{m} - \phi_{13}^{k}\right|\right\} \end{cases}$$

according to

$$\left(\left|\kappa_{z12}\right| - \left|\kappa_{z13}\right|\right)\left(\left|\Delta\phi_{12}{}^{mk}\right| - \left|\Delta\phi_{13}{}^{mk}\right|\right) \geq 0$$

$$and \qquad Min\left\|\Delta\phi_{12}{}^{mk}\right|\left|\kappa_{z13}\right| - \left|\Delta\phi_{13}{}^{mk}\right|\left|\kappa_{z12}\right\|^{2}$$

$$\sin ce \quad \Delta h^{mk} = \left|\Delta\phi_{12}{}^{mk}\right| / \left|\kappa_{z12}\right| = \left|\Delta\phi_{13}{}^{mk}\right| / \left|\kappa_{z13}\right|$$

Dual-baseline solution

- height difference estimation using least square method

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

$$\Rightarrow \qquad h_V = Max\left(\left|\Delta h^{mk}{}_{est}\right|\right)$$

Height difference between ground and canopy is the largest.

Suppress phase errors

Ref. Cloude SR. and Papathanassiou KP Three-stage inversion process for polarimetric SAR Interferometry. 2003.

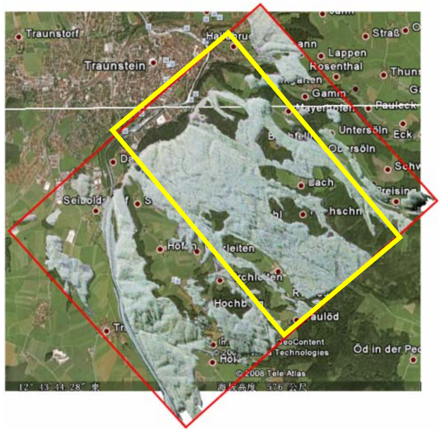
Outline

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

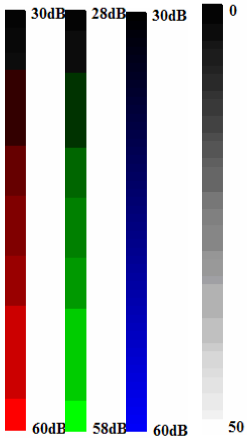
Experimental Data

- 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

HH HV VV



Google Earth Map

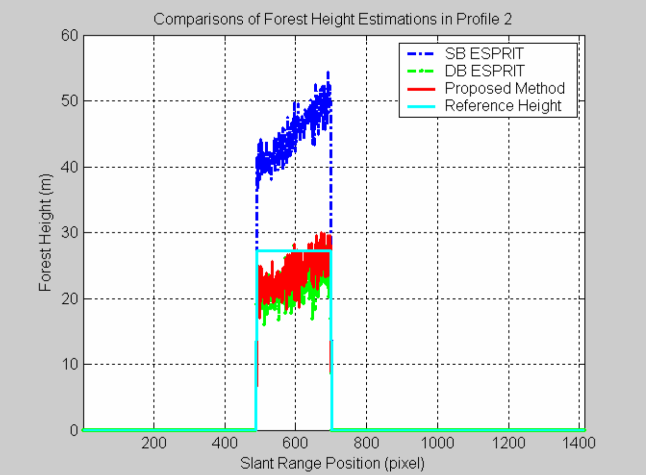


Experiment Design

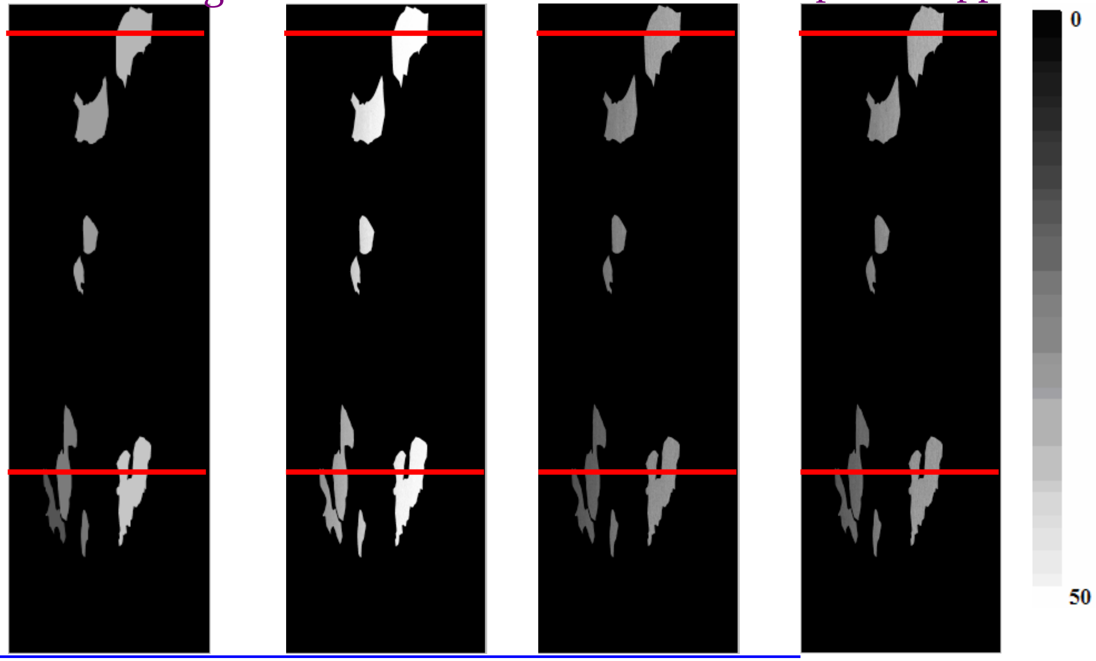
- SB ESPRIT (B13) vs DB ESPRIT(B12-B13)
  - DB ESPRIT
    - Centers' number estimated from Coherence optimization
    - separate signal subspaces
    - estimate forest height
  - analyze the improvement brought by additional baseline
- DB ESPRIT vs Proposed Approach
  - DB ESPRIT
    - Centers' number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

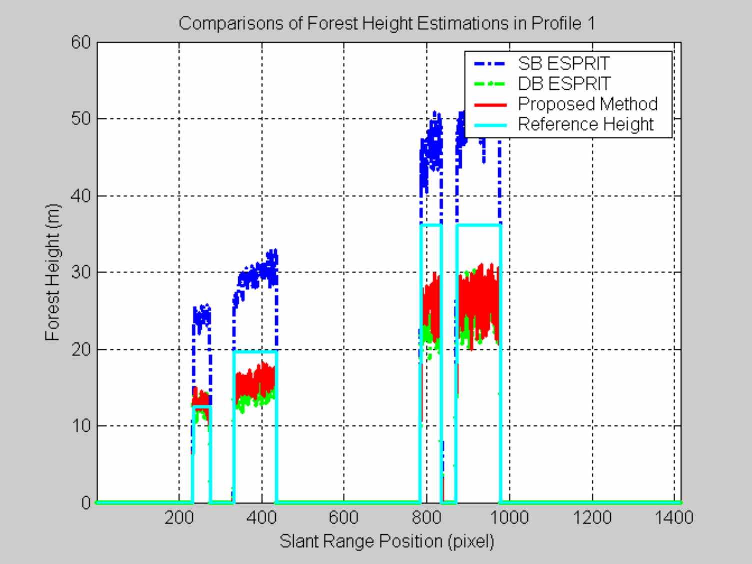
EXPERIMENTAL RESULTS

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



Reference height SB ESPRIT DB ESPRIT Proposed Approach





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

Test Areas		SB ESPRIT	DB ESPRIT	Proposed Approach
Indicator	**Reference Height**	**Average Height**	**Average Height**	**Average Height**
T1	**32.49**	56.54	27.35	**29.43**
T2	**27.20**	44.79	21.77	**23.73**
T3	**26.30**	42.31	20.77	**22.43**
T4	**27.32**	38.02	18.81	**20.39**
T5	**19.68**	29.47	14.50	**15.79**
T6	**36.10**	48.43	23.90	**25.68**
T7	**12.46**	26.95	13.24	**14.31**
T8	**18.66**	35.87	17.90	**19.16**

EXPERIMENTAL RESULTS

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

Test Areas		SB ESPRIT	DB ESPRIT	Proposed Approach
Indicator	**Reference Height**	**Deviation (m)**	**Deviation (m)**	**Deviation (m)**
T1	**27.35**	24.74	7.38	5.92
T2	**21.77**	11.64	13.33	11.48
T3	**20.77**	15.64	7.52	6.06
T4	**18.81**	11.61	8.79	7.27
T5	**14.50**	4.33	12.09	10.82
T6	**23.90**	21.60	5.68	4.63
T7	**13.24**	6.90	20.07	19.01
T8	**17.90**	6.63	12.60	11.40

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

$$\Delta\phi = Max\left\{\left|\phi^1 - \phi^2\right|, 2\pi - \left|\phi^1 - \phi^2\right|\right\}$$

    - Three Stable Scattering Center
      - Phase difference between ground and canopy is the largest
      - Errors Caused by Phase Unwrapping

$$\Delta\phi = \max\left\{\left|\phi^m - \phi^k\right|, 2\pi - \left|\phi^m - \phi^k\right|\right\} \qquad m, k = 1, \ldots, d$$

  - Forest Height Estimation

$$h_V = \frac{\Delta\phi}{\left|\kappa_z\right|}$$

EXPERIMENTAL RESULTS

- SB ESPRIT
  - Considering Phase Unwrapping (1)

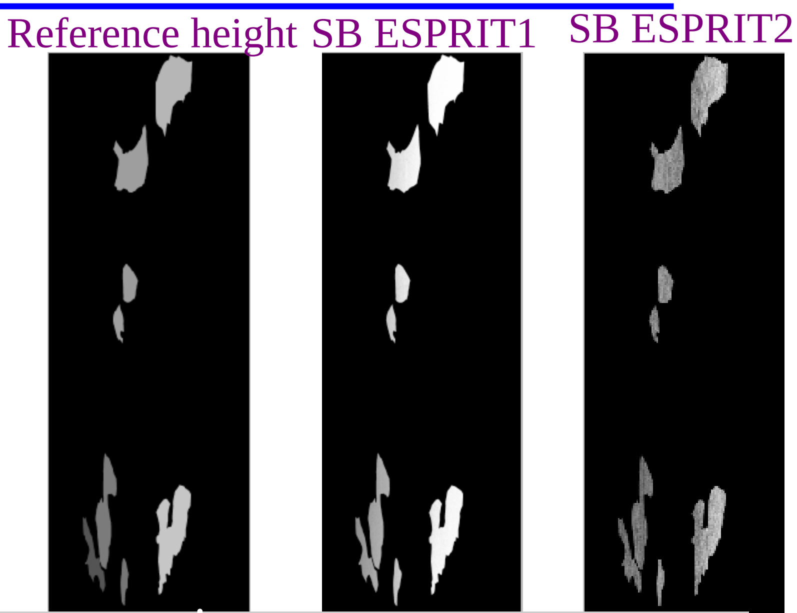
$$\Delta\phi = Max\left\{\left|\phi^m - \phi^k\right|, 2\pi - \left|\phi^m - \phi^k\right|\right\}$$

$$m,k = 1,\ldots,d$$

  - Neglect Phase Unwrapping (2)

$$\Delta\phi = Max\left\{\left|\phi^m - \phi^k\right|\right\}$$

$$m,k = 1,\ldots,d$$



Test Areas		**SB ESPRIT 1**		**SB ESPRIT 2**	
Indicator	Reference Height	Average Height	Height Deviation	Average Height	Height Deviation
T1	32.49	56.54	24.74	29.2579	14.2827
T2	27.20	44.79	11.64	23.1616	15.5306
T3	26.30	42.31	15.64	23.5839	10.7318
T4	27.32	38.02	11.61	22.3948	11.0181
T5	19.68	29.47	4.33	18.0151	11.7038
T6	36.10	48.43	21.60	28.1808	13.2466
T7	12.46	26.95	6.90	18.3178	16.8094
T8	18.66	35.87	6.63	24.7882	11.0768

Outline

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

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

Thank You !

Please contact via e-mail: bailu81@gmail.com

National Key Laboratory of
Microwave Imaging Technology
Beijing, 100190, P. R. China

Institute of Electronics,
Chinese Academy of Sciences
Beijing, 100190, P. R. China