→ 3rd ADVANCED COURSE ON RADAR POLARIMETRY

PolSAR-Ap: Basic Principles of SAR Polarimetry

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Motivation

- SAR Polarimetry is characterized by Mathematical and Signal Processing backgrounds that need to be correctly introduced for a better understanding of the applications and the extraction of quantitative biophysical and geophysical parameters

- Reviewed and complemented theoretical background with new topics and new references (publications, books) according to the different applications selected to illustrate the PolSAR Application Demonstration

- Establishment of a common mathematical formulism

- To provide a self-contained manuscript

- Limited theoretical view. Introduction on basic concepts and ideas necessary for a complete analysis and development of the different applications selected to illustrate the PolSAR Application Demonstration

Basic Aspects Presented

- Theory of Radar Polarimetry
  - Wave polarimetry
  - Scattering polarimetry
- SAR Data Statistical Description and Speckle Noise Filtering
  - Statistical characterization of PolSAR data
  - Definition of the polarimetric coherence and the Covariance and Coherency matrices
  - Polarimetric Speckle Noise Filtering
- Polarimetric Scattering Decomposition Theorems
- Polarimetric SAR Interferometry
- Polarimetric SAR Tomography
- References

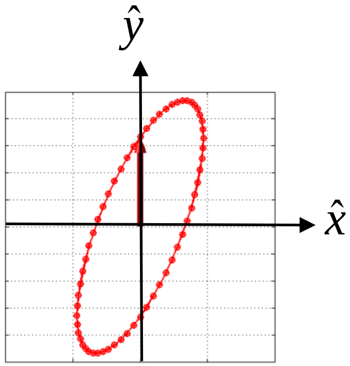
Theory of Radar Polarimetry

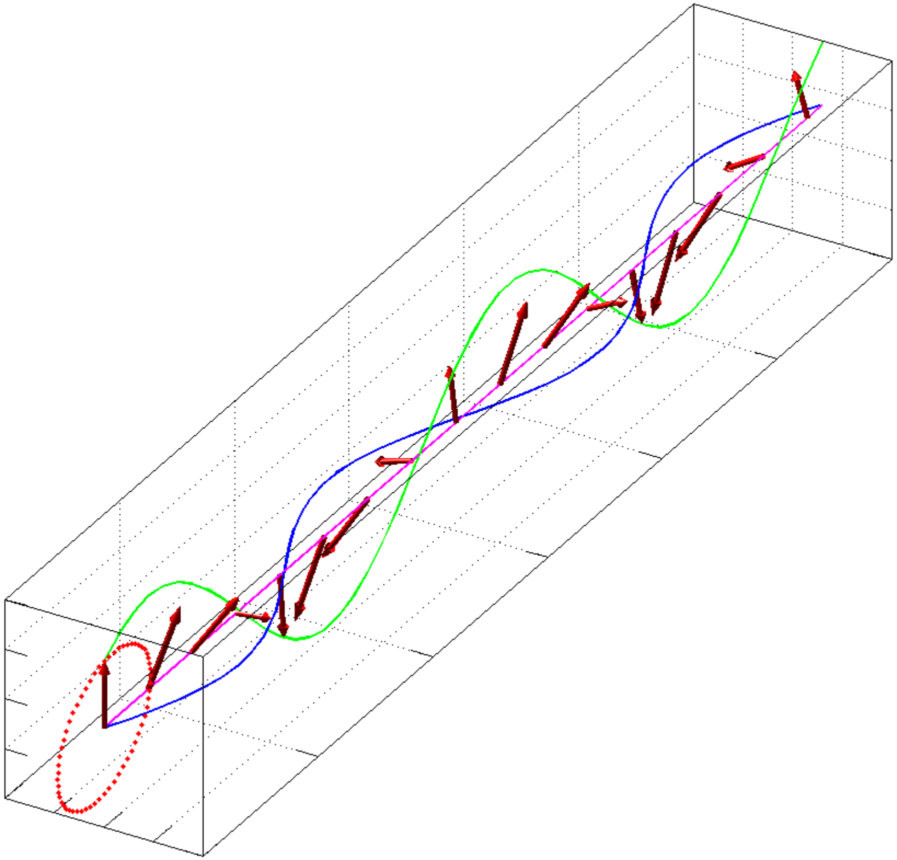
- Definition: **Polarimetry** refers specifically to the vector nature of the electromagnetic waves, whereas radar polarimetry is the science of acquiring, processing and analyzing the polarization state of an electromagnetic wave in radar applications:
  - **Wave polarimetry** that deals with the representation and the understanding of the polarization state of an electromagnetic wave
  - **Scattering polarimetry** collects the topic of inferring the properties of a given target, from a polarimetric point of view, given the incident and the scattered polarized electromagnetic waves

Theory of Radar Polarimetry

- Starting Point: Space-Time evolution of the real electromagnetic field
  Electromagnetic field

$$\vec{E}(z,t)=\begin{cases} E_x = E_{0x}\cos\left(\omega t - kz - \delta_x\right) \\ E_y = E_{0y}\cos\left(\omega t - kz - \delta_y\right) \\ E_z = 0 \end{cases}$$



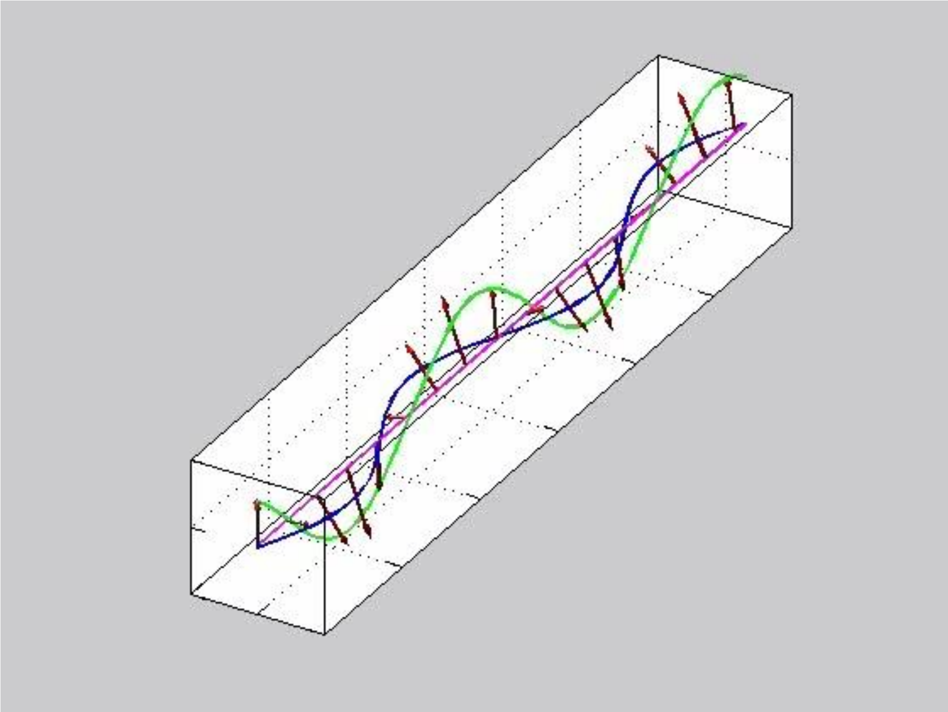


Polarization Ellipse for z_0

Theory of Radar Polarimetry

- Starting Point: Space-Time evolution of the real electromagnetic field Electromagnetic field

$$\vec{E}(z,t)=\begin{cases} E_x = E_{0x}\cos\left(\omega t - kz - \delta_x\right) \\ E_y = E_{0y}\cos\left(\omega t - kz - \delta_y\right) \\ E_z = 0 \end{cases}$$



Theory of Radar Polarimetry

- Description of the polarization ellipse
  - Totally polarized waves
    - Geometrical description
    - Jones vector
    - Stokes vector
    - Description of the canonical polarization states (linear, circular, …)
  - Partially polarized waves
    - Coherency matrix/vector
    - Stokes vector

- Change of polarization basis and Polarization Synthesis

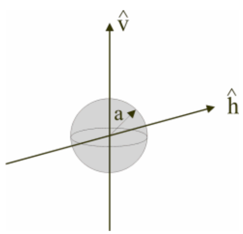
$$\begin{bmatrix} E_u \\ E_{u\perp} \end{bmatrix} = \mathbf{U}^{-1}_{\{\hat{\mathbf{u}},\hat{\mathbf{u}}_\perp\}} \begin{bmatrix} E_x \\ E_y \end{bmatrix}$$

Theory of Radar Polarimetry

- Scattering polarimetry: Introduction of the concept of scattering matrix

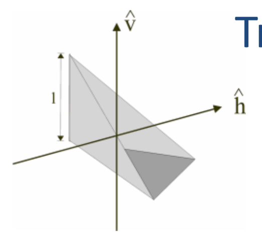
$$\begin{bmatrix} E_h^s \\ E_v^s \end{bmatrix} = \frac{e^{-jkr}}{r} \begin{bmatrix} S_{hh} & S_{hv} \\ S_{vh} & S_{vv} \end{bmatrix} \begin{bmatrix} E_h^i \\ E_v^i \end{bmatrix}$$

- Introduction of conventions
  - Forward scattering
  - Backscattering
  - FSA Alignment convention
  - BSA Alignment convention
- Canonical scattering mechanisms



Sphere

$$\mathbf{S} = \frac{a}{2} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$



Trihedral Corner Reflector

$$\mathbf{S} = \frac{kl^2}{\sqrt{12\pi}} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

Theory of Radar Polarimetry

- Key concept: Scattering vector, i.e., vectorization of the scattering matrix

$$\mathbf{k}_l = \begin{bmatrix} S_{hh} \\ S_{hv} \\ S_{vh} \\ S_{vv} \end{bmatrix} \quad \mathbf{k}_p = \frac{1}{\sqrt{2}} \begin{bmatrix} S_{hh} + S_{vv} \\ S_{hh} - S_{vv} \\ S_{hv} + S_{vh} \\ j\left(S_{hv} - S_{vh}\right) \end{bmatrix} \qquad \mathbf{k}_l = \begin{bmatrix} S_{hh} \\ \sqrt{2} S_{hv} \\ S_{vv} \end{bmatrix} \quad \mathbf{k}_p = \frac{1}{\sqrt{2}} \begin{bmatrix} S_{hh} + S_{vv} \\ S_{hh} - S_{vv} \\ 2S_{hv} \end{bmatrix}$$

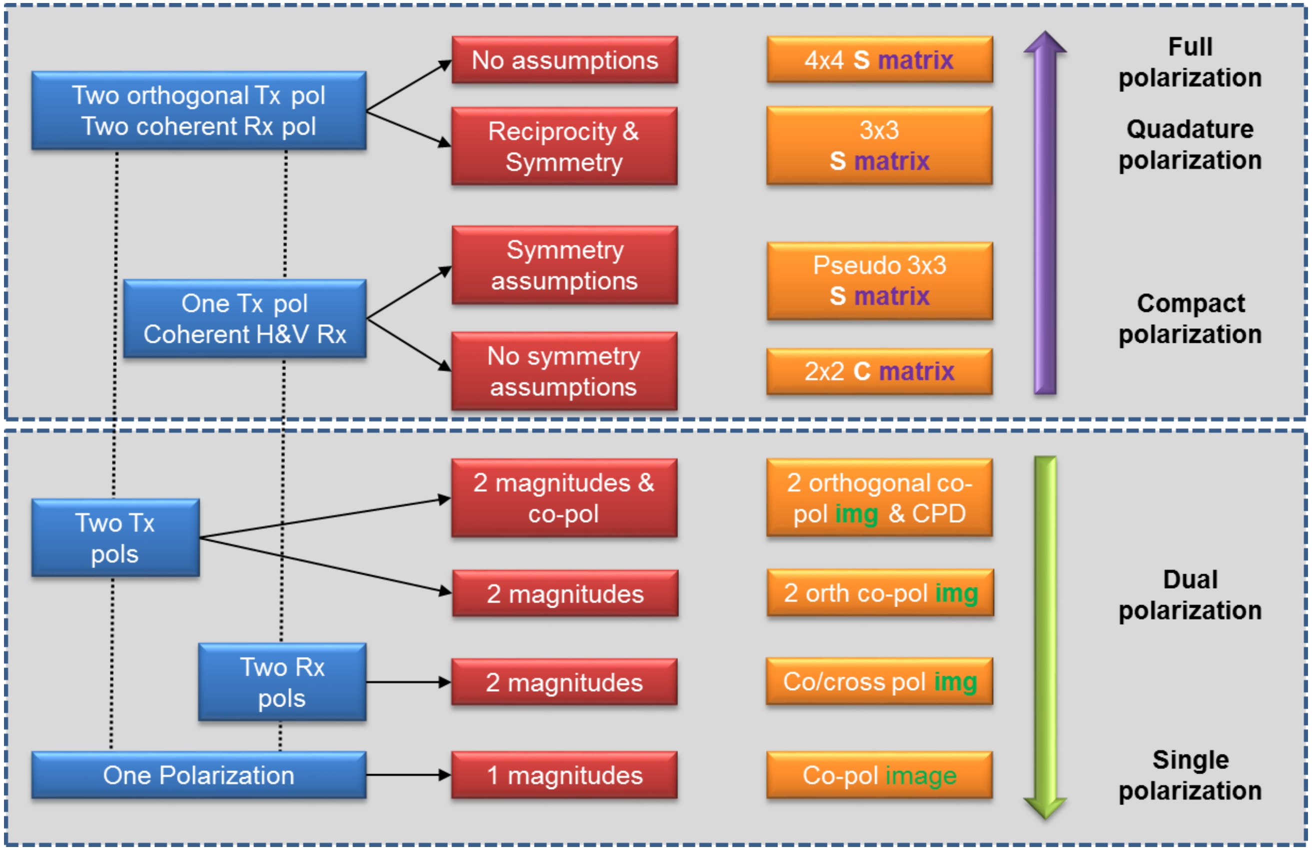
- Key concept: Hermitian product of target vector (backscattering direction under the BSA convention)

$$\mathbf{k}_l \mathbf{k}_l^{T*} = \begin{bmatrix} \left|S_{hh}\right|^2 & \sqrt{2} S_{hh} S_{hv}^* & S_{hh} S_{vv}^* \\ \sqrt{2} S_{hv} S_{hh}^* & \left|S_{hv}\right|^2 & \sqrt{2} S_{hv} S_{vv}^* \\ S_{vv} S_{hh}^* & \sqrt{2} S_{vv} S_{hv}^* & \left|S_{vv}\right|^2 \end{bmatrix}$$

$$\mathbf{k}_p \mathbf{k}_p^{T*} = \begin{bmatrix} \left|S_{hh} + S_{vv}\right|^2 & \left(S_{hh} + S_{vv}\right)\left(S_{hh} - S_{vv}\right)^* & 2\left(S_{hh} + S_{vv}\right) S_{hv}^* \\ \left(S_{hh} - S_{vv}\right)\left(S_{hh} + S_{vv}\right)^* & \left|S_{hh} - S_{vv}\right|^2 & 2\left(S_{hh} - S_{vv}\right) S_{hv}^* \\ 2S_{hv}\left(S_{hh} + S_{vv}\right)^* & 2S_{hv}\left(S_{hh} - S_{vv}\right)^* & 4\left|S_{hv}\right|^2 \end{bmatrix}$$

Theory of Radar Polarimetry

- Single, Dual, Compact and Full Polarimetry



Courtesy of Dr. R. K. Raney

SAR Data Statistical Description

- Starting point: Speckle noise scattering model or Random Walk. Constructive and destructive interference that appears in coherent imaging systems

Radarsat-2 amplitude image o the scattering matrix element S_{hh} over San Francisco (USA)

- SAR data must be considered statistically to account fot the speckle noise effect
  - One-dimensional Gaussian distribution (Single SAR image)
  - Multidimensional Gaussian distriibution (Target vectors)

SAR Data Statistical Description

- Key concept: The Covariance and the Coherency matrices (backscattering direction under the BSA convention)

$$\mathbf{C}=E\left\{\mathbf{k}_l\mathbf{k}_l^{T*}\right\}=\begin{bmatrix} E\left\{|S_{hh}|^2\right\} & E\left\{\sqrt{2}S_{hh}S_{hv}^*\right\} & E\left\{S_{hh}S_{vv}^*\right\} \\ E\left\{\sqrt{2}S_{hv}S_{hh}^*\right\} & E\left\{|S_{hv}|^2\right\} & E\left\{\sqrt{2}S_{hv}S_{vv}^*\right\} \\ E\left\{S_{vv}S_{hh}^*\right\} & E\left\{\sqrt{2}S_{vv}S_{hv}^*\right\} & E\left\{|S_{vv}|^2\right\} \end{bmatrix}$$

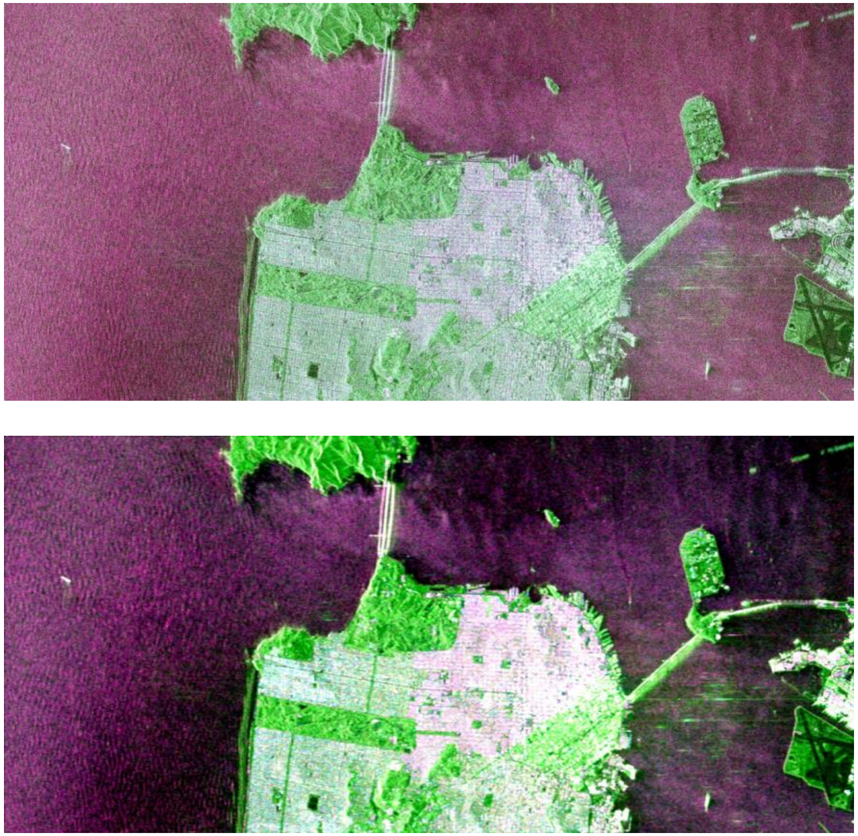
$$\mathbf{T}=E\left\{\mathbf{k}_p\mathbf{k}_p^{T*}\right\}=\begin{bmatrix} E\left\{|S_{hh}+S_{vv}|^2\right\} & E\left\{(S_{hh}+S_{vv})(S_{hh}-S_{vv})^*\right\} & E\left\{2(S_{hh}+S_{vv})S_{hv}^*\right\} \\ E\left\{(S_{hh}-S_{vv})(S_{hh}+S_{vv})^*\right\} & E\left\{|S_{hh}-S_{vv}|^2\right\} & E\left\{2(S_{hh}-S_{vv})S_{hv}^*\right\} \\ E\left\{2S_{hv}(S_{hh}+S_{vv})^*\right\} & E\left\{2S_{hv}(S_{hh}-S_{vv})^*\right\} & E\left\{4|S_{hv}|^2\right\} \end{bmatrix}$$

- Key concept: The polarimetric coherence

$$\rho=|\rho|e^{j\phi_x}=\frac{E\left\{S_kS_l^*\right\}}{\sqrt{E\left\{|S_k|^2\right\}E\left\{|S_l|^2\right\}}}$$

SAR Data Statistical Description

- Speckle noise filtering: Estimation of the Covariance and Coherency matrices



Radarsat-2 polarimetric RGB image over San Francisco (USA) where the colour code is: Shh blue, Svv red and Shv green. (a) Original image and (b) Filtered image with a 7x7 multilook filter

|Svv| |Shv| |Shh|

Polarimetric Target Decomposition Theorems

- Decomposition of the Scattering or the Coherency and Covariance matrices for a better interpretation
  - Coherent Target Decomposition Theorems

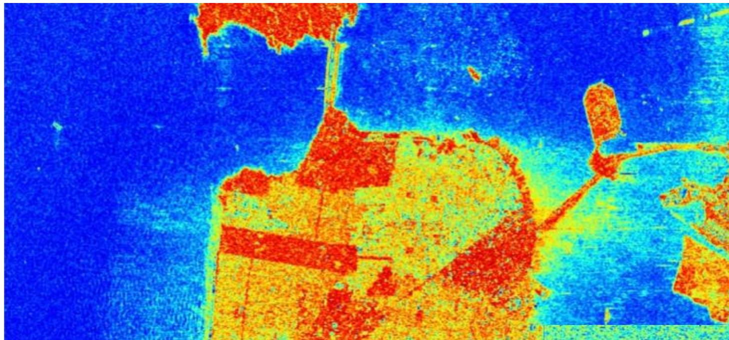
$$\mathbf{S} = \sum_{i=1}^{k} c_i \mathbf{S}_i$$

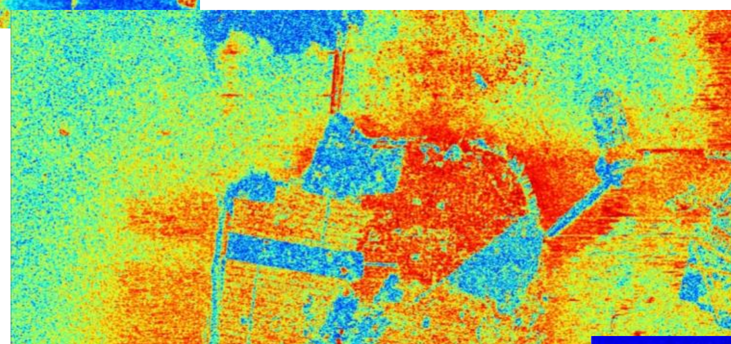
    - Pauli decomposition
  - Incoherent Target Decomposition Theorems

$$\mathbf{C} = \sum_{i=1}^{k} p_i \mathbf{C}_i \qquad \mathbf{T} = \sum_{i=1}^{k} q_i \mathbf{T}_i$$

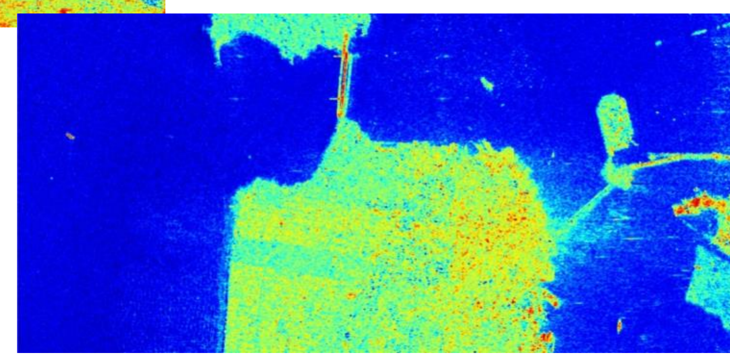
    - Three-component Freeman Decomposition
    - Four-Component Yamaguchi Decomposition
    - Non-Negative Eigenvalue Decomposition
    - Eigenvector-Eigenvalue based Decomposition (Entropy, Anisotropy and Mean Alpha Angle)

Polarimetric Target Decomposition Theorems





Radarsat-2 polarimetric RGB image over San Francisco (USA)



Polarimetric SAR Interferometry

- Study variation of the interferometric coherence with polarization to study volumetric scatterers
  - Single Channel Interferometry

$$\gamma = |\gamma| e^{i\phi} = \frac{E\left\{S_1 S_2^*\right\}}{\sqrt{E\left\{S_1 S_1^*\right\}}\sqrt{E\left\{S_2 S_2^*\right\}}}$$

  - Multi Channel Interferometry

$$\mathbf{\Lambda}_1 = \mathbf{T} \rightarrow \mathbf{\Lambda}_2 = \begin{bmatrix} \mathbf{T}_{11} & \mathbf{\Omega}_{12} \\ \mathbf{\Omega}_{12}^H & \mathbf{T}_{22} \end{bmatrix} \qquad \gamma\left(\mathbf{w}_1, \mathbf{w}_2\right) = \frac{\mathbf{w}_1^H \mathbf{\Omega}_{12} \mathbf{w}_2}{\sqrt{\mathbf{w}_1^H \mathbf{T}_{11} \mathbf{w}_1} . \sqrt{\mathbf{w}_2^H \mathbf{T}_{22} \mathbf{w}_2}}$$

    - Optimization of interfeometric coherence (Max and Mins)
    - Model based PolInSAR: Random Volume over Ground Model (RVoG)

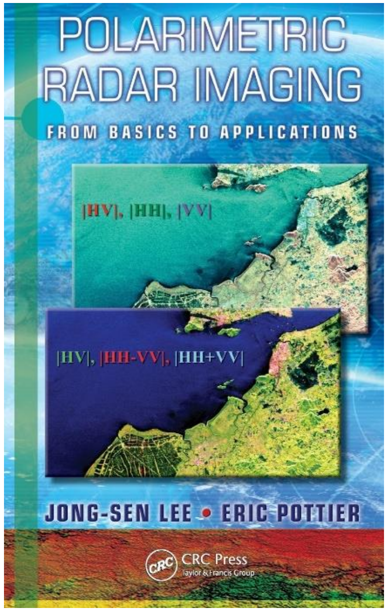
Polarimetric SAR Tomography

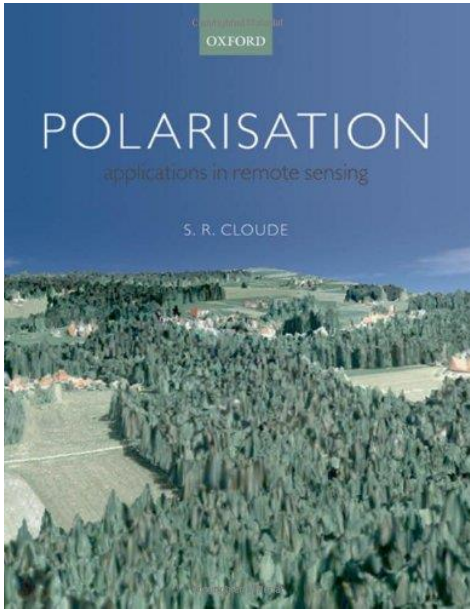
- Key concept: 3-D SAR Tomography (SARTom) is an experimental multibaseline (MB) interferometric mode achieving full 3-D imaging in the range-azimuth-height space through elevation beam forming, i.e. spatial (baseline) spectral estimation
  - SARTom can add more features for the analysis of complex scenarios, e.g. for the estimation of forest height and biomass, sub-canopy topography, soil humidity and ice thickness monitoring, and extraction of heights and reflectivities in layover urban areas
  - Polarimetric SAR Tomgraphy (PolSARtom) jointly exploits MB SAR data acquired with different polarization channels to improve the accuracy of the estimation of the vertical position of the imaged scatterers, and to estimate a set of normalized complex coefficients characterizing the corresponding polarimetric scattering mechanism

- Aspects descrived:
  - SARtom and PolSARTom as Spectral Estimation Problems: Non-model Based Adaptive Solutions
  - Model-based PolTomSAR
  - Coherence Tomography

Conclusions

- Limited theoretical view. Introduction on basic concepts and ideas necessary for a complete analysis and development of the different applications selected to illustrate the PolSAR Application Demonstration
- Complete theoretical view as references/bibliography. Main references:





- Complementarity with other books