Lecture 11: Concepts of Polarimetric SAR

Polarization States of a Coherent Plane Wave

- Vertically polarized
- Horizontally polarized
- Electric field vector
**Linearly Polarized Signals**

- Several stages of linear polarization possible
  - Horizontal polarization (a)
  - Vertical polarization (b)
  - Linear -45° polarization (c)
  - Linear +45° polarization (d)

**Circular and Elliptical Polarization**

- Combination of vertically and horizontally polarized signals
  - Right circular polarization (a)
  - Left circular polarization (b)
  - Right elliptical polarization (c)
  - Left elliptical polarization (d)

**Polarization of SAR Systems**

- HH: Horizontal Transmit, Horizontal Receive
- VV: Vertical Transmit, Vertical Receive
- VH: Vertical Transmit, Horizontal Receive
- HV: Horizontal Transmit, Vertical Receive
- Co-Polarized
- Cross-Polarized
Polarimetric SAR System Configurations

- **single pol:**
  - VV or HH (or possibly HV or VH)

- **dual pol:**
  - HH and HV, VV and VH, or HH and VV

- **quad pol (fully polarimetric):**
  - HH, VV, HV, and VH

Relative phase between channels is important information.
In a quad-pol SAR, every pixel is represented by a matrix of four complex numbers, representing ratios of received and transmitted electric-field amplitudes:

\[
\begin{pmatrix}
S_{VV} & S_{VH} \\
S_{HV} & S_{HH}
\end{pmatrix}
\]

(scattering or Jones matrix)

For (monostatic) SARs: \( S_{VV} = S_{HH} \) (reciprocity)

\[
\begin{pmatrix}
S_{VV} & S_{VH} \\
S_{HV} & S_{HH}
\end{pmatrix}
\]

(Sinclair matrix)

\( \Rightarrow 3 \) amplitudes + 2 independent phases per pixel

To Make Sense of Polarization, It Is Convenient to Assume that the World is Made Up of Three Different Types of Targets

- Radar scattering is physical and can be described as a series of bounces on scattering interfaces
- Three main scattering mechanisms dominate:
  - Scattering on (rough) surfaces: Water, bare soils, rock – Scattering strongly dependent on surface roughness and sensor wavelength
  - Double-bounce scattering: Buildings, tree trunks, light poles – Little wavelength dependence
  - Volume scattering: Vegetation, dry soils with high penetration – Strongly dependent on sensor wavelength and dielectric properties of medium
Scattering Processes: Rough Surface (Bragg) Scattering

- Polarimetric Dependence of Bragg scattering:
  - Horizontal polarization:
    \[ R_{HH} = m \frac{\epsilon}{\cos^2 \theta - \sin^2 \theta} \]
  - Vertical polarization:
    \[ R_{VV} = m \frac{\cos^2 \theta - \sin^2 \theta}{\epsilon} \]
  - Cross polarizations:
    \[ R_{HV} = R_{VH} = 0 \]

where \( \epsilon \) is the dielectric constant of the surface and \( m \) depends on surface roughness.

Scattering Matrix:
\[
\begin{bmatrix}
R_{HH} & 0 \\
0 & R_{VV}
\end{bmatrix}
\]

Scattering Processes: Fresnel Reflection

- Fresnel Reflection Coefficients:
  \[ R = \cos \frac{2\pi}{\lambda} \frac{\epsilon}{\cos \theta} \]
  \[ T = \frac{1 - R}{\cos \theta} \]

where \( \epsilon \) is the dielectric constant of the surface.

This explains direct reflection off smooth surfaces.
### Polarimetric Dependence of Scattering Principles

Relative scattering strength by polarization:

- **Pure Surface Scattering:** $|S_{HH}| > |S_{HV}| > |S_{VV}|$
- **Double Bounce Scattering:** $|S_{HH}| > |S_{VV}| > |S_{HV}|$
- **Volume Scattering:** main source of $|S_{HV}|$ and $|S_{VV}|$

### Visual Interpretation

- Simplest method for classifying polarimetric imagery
- Present data in a color image to support interpretation
- Suggested “realistic looking” color assignment:
  - HH = red
  - HV = green
  - VV = blue
  - Water reflections have high VV
  - Vegetation has higher than average HV

### Think – Pair – Share

- Color composite of an ALOS PALSAR (L-band) scene over Washington, DC
- The following color coding was applied:
  \[
  z = \begin{cases}
  S_{HH} & \text{red} \\
  S_{HV} & \text{green} \\
  S_{VV} & \text{blue}
  \end{cases}
  \]

- **Q1:** What are the red areas in this image?
- **Q2:** What may cause this region to appear white?
- **Q3:** This is a river. Why does it appear in a purple color rather than blue?
Sinclair Decomposition

- **Definition:**
  - $\mathbf{s} = \begin{bmatrix} S_{uu} \\ S_{uv} \\ S_{vu} \\ S_{vv} \end{bmatrix}$

- **Example:**
  - ALOS PALSAR (L-band) data over Washington, D.C.

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Example of Multiple Polarizations for Vegetation Studies - Pacaya-Samiria Forest Reserve in Peru

- L-band SAR images from UAVSAR (HH, HV, VV)

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SAR Signatures of Vegetation at Various Frequencies and Polarizations

- Polometric signature change and sub-canopy features are exposed as wavelength increases.

Polarimetric Signatures of Different Types of Agricultural Crops

- The structure of crops/vegetation defines scattering power at different polarizations:
  - Voluminous leafy vegetation will scatter strongly in HV
  - Stemmy vegetation (e.g., corn) will dominate in HH
  - Bare fields and low vegetation stronger in VV

Example:
JPL UAVSAR image acquired by L-band radar showing three backscatter polarizations and the false-colored composites over an area in California's Central Valley covered by orchards and different crops. The strength of each polarized backscatter is shown, relatively suggesting how certain crops are relatively higher in one of the HH, HV, and VV polarizations.

Different Ways Of Representing Polarimetric Data

- Commonly used polarimetric target descriptors include:
  - $[S]$ Sinclair matrix
  - $k$ Pauli Scattering Vector
  - $[K]$ Kennaugh Matrix
  - $[T]$ Coherency Matrix
  - $[C]$ Covariance Matrix

- Pauli Vector, Kennaugh matrix, and Coherency matrix are closely related to physical properties of the scatter
  → allow insight into surface structure

- Sinclair Matrix and Covariance matrix are directly related to the system measurables

The Pauli Scattering Vector

- The Scattering matrix can be decomposed by a set of "Pauli Matrices" $Y_P$ resulting in the Paul vector $k$
  \[ k = \frac{1}{2} \text{tr}(S_P) \]

- Resulting in:
  \[ k = \frac{1}{2} \left( S_{HH} + S_{HV} - S_{HH} - S_{HV} \right) \]

- Surface scattering  Double bounce scattering  Volume scattering

Related to physical properties of the scatterers
The Pauli Scattering Vector

- In the monostatic case (where you can assume that HV = VH) the Pauli Vector reduces to three elements:

\[ \mathbf{S} = \begin{bmatrix} S_{HH} - S_{VV} \\ S_{HV} \\ S_{VH} + S_{HH} \end{bmatrix} \]

- It makes sense to represent these parameters in an RGB image with red = double bounce, green = volume scattering, and blue = single bounce.

The Pauli Vector – A Polarimetric Decomposition

- Technically speaking, the Pauli Vector is a "Polarimetric Decomposition":
  - Take a complex matrix of correlated parameters
  - Decompose into sum of (orthogonal) component matrices, each of which has some simpler physical interpretation

- Typical Decomposition Techniques include:
  - Cholesky decomposition
  - Eigenvector decomposition
  - Singular Value Decomposition
  - Pauli Decomposition
  - …

- Goals: Decompose complex correlated measurements into uncorrelated components that are easier to interpret.

Pauli & Sinclair Decomposition

- Patterns: HH, HV, VH
- Interpretation: double bounce, volume, single bounce

- Patterns: HH, HV + VH
- Interpretation: preferred double bounce, preferred surface
Scene Classification based on Polarimetric Decompositions

- **Unsupervised classifiers** have been introduced in the recent years
  - Based on physical properties of target and dominant scattering mechanism and NOT on dataset
  - No prior knowledge about scene content or terrain classes necessary

- **Main decomposition-based classifiers**:
  - Van Zyl: "odd bounce," "even bounce," "diffuse"
  - Freeman: Three component scattering model-based classification
  - Cloude & Pottier: H / A Classifier
  - Cloude & Pottier: H / A / a Classifier
  - Yamaguchi: Four Component scattering model-based classification (extension of Freeman)

- Newest methods combine unsupervised methods (e.g., H / A) with a subsequent supervised classifier to improve results

### The Unsupervised H / a Classifier

- **Eigendecomposition** of the coherency matrix (i.e., reduction large number of parameters into an orthogonal set of parameters that contain meaningful information) → Physical interpretation of Eigenvalues

  - **Polarimetric Entropy (H)** (calculated from ratio of Eigenvalues):
    - Represents randomness of scattering with H = 0 indicates single scattering mechanism and H = 1 represents random mix of mechanisms

  - **The (average) a-Angle** (calculated from Eigenvector): Indicative of dominant scattering mechanism
    - If $\alpha < 0°$ → surface scattering
    - If $\alpha = 45°$ → volume scattering
    - If $\alpha > 90°$ → dihedral or multiple scattering

\[ a = \frac{\sum_{i=1}^{3} \alpha_i P_i}{3} \]

\[ \alpha_i = \text{angle relative to vertical} \]
The Unsupervised H / α Classifier

- The H/α diagram is shown below
- By definition, all image pixels will have H/α values within the feasible region

Example of SAR Data in H / α Diagram

- TerraSAR-X SAR Data
- Agricultural Fields are shown
- Data Characteristics:
  - Spread across a range of H values with average of H ≈ 0.8
  - Low α indicates dominance of surface scattering
  - Indications of variations of crop density on fields

The Unsupervised H / α Classifier

- The H/α plane is partitioned into nine classes
- Classes are chosen on general properties of scattering
Refinement: The Unsupervised H / A / $\alpha$ (Entropy/Anisotropy/Alpha) Classifier

- In cases of high Entropy ($H > 0.7$), the H / $\alpha$ classification scheme is not unique.
- E.g. we cannot discriminate between the following scattering cases:

$$H = 0.8 \quad H = 0.8$$

- Anisotropy was introduced to solve these problems by distinguishing cases where $l_2 \approx l_3$ from cases where $l_2$ is large and $l_3$ is small.

Complementary to Entropy $H$

Additional discrimination when $H > 0.7$

Refinement 2: Rotation Angle Correction of Polarimetric Signatures

- Scattering matrix for even-bounce scatterers:

$$
\begin{bmatrix}
  1 & 0 & 0 \\
  0 & 1 & 0 \\
  0 & 0 & 0
\end{bmatrix}
$$

- If scatterer oriented parallel to flight track:

$$
\begin{bmatrix}
  1 & 0 & 0 \\
  0 & 1 & 0 \\
  0 & 0 & 0
\end{bmatrix} = R \begin{bmatrix}
  1 & 0 & 0 \\
  0 & 1 & 0 \\
  0 & 0 & 0
\end{bmatrix} R
$$

- In case of rotation with angle $\phi$:

$$
\begin{bmatrix}
  1 & 0 & 0 \\
  0 & 1 & 0 \\
  0 & 0 & 0
\end{bmatrix} = R \begin{bmatrix}
  1 & 0 & 0 \\
  0 & 1 & 0 \\
  0 & 0 & 0
\end{bmatrix} R
$$

Rotation of dihedral scatterers makes dihedrals look like volume scatterers.


Correction of Rotation Based on Deorientation Concept of Huygens

Minimization of cross-polarized HV component
<table>
<thead>
<tr>
<th>Location</th>
<th>Date</th>
<th>Coordinates</th>
<th>Image ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fugen-dake Unzen, Japan</td>
<td>2007/6/5</td>
<td>32.825N; 130.364E</td>
<td>ALPSRP072570650-1.1A</td>
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<td>39.747N; 140.976E</td>
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<td>Bangladesh</td>
<td>2009/04/08</td>
<td>21.923N; 89.904E</td>
<td>ALPSRP224000430</td>
</tr>
</tbody>
</table>
Available Software Tools

- PolSARPro is a freely available software tool provided by ESA
  - Can be downloaded at: https://earth.esa.int/web/polsarpro/home
  - It includes all available polarimetric decomposition methods for dual-pol and quad-pol SAR data
  - In addition to the software also tutorials to Polarimetry can be downloaded
  - Includes polarimetric analysis of Sentinel-1 dual-pol data

EXAMPLES OF SAR IMAGE CLASSIFICATION

The H / α Classifier

- Mixed natural environment in Germany

Optical Image  Polarmetric SAR color composite
The H / α Classifier

Example Natural Environment

- Mixed natural environment in Germany

Entropy

Alpha angle [º]

Vegetation

Rough Surface

Needles

Branches

Double bounce in forests

Bragg Surface

Dihedral Scattering

Segmentation Result

Courtesy: I. Hajnsek/DLR

The H / α Classifier

Example: San Francisco Bay Area

Segmentation Result

Courtesy: I. Hajnsek/DLR
The H/α Classifier

Example: San Francisco Bay Area

Pauli representation
The H / A / α Classifier
Example: San Francisco Bay Area

Unsupervised Classification based on the H / A / α Decomposition

- Example of k-mean classification procedure:

Unsupervised Classification based on the H / A / α Decomposition

- Disadvantage of H / A / α classification schemes:
  - H / α classification space is sub-divided into 9 basic zones
  - Location of the boundaries is fairly arbitrary and generic
  - Therefore, H / A / α classification is not optimal and more advanced ways for determining class boundaries are sought.

- Solution:
  - In newer approaches H / A / α classification results are combined with a subsequent Wishart or maximum likelihood classification to improve performance.
  - H / A / α classification results provide initial class centers that are improved in subsequent classification.
Unsupervised Classification based on the H/A/α Decomposition

• Example of k-mean classification procedure:

Unsupervised Classification based on the H/A/α Decomposition

H/α = subsequent classifier

H/α only

Performance improvement

Polarimetric Classification

The Role of the Observation Frequency

Different penetration in different frequencies produce different polarimetric signatures

Australian Pasture

Polarimetric data is volume dominated

Courtesy of J. Lee
Polarimetric Classification
The Role of the Observation Frequency

- Different penetration in different frequencies produce different polarimetric signatures

Australian Pasture
Courtesy: J.S. Lee

What’s Next?

- Next lecture we will talk about SAR Interferometry (InSAR).
- In preparation for this lecture please read the following pages in Woodhouse (2006):
  - Pages 312-311: Radar Interferometry