SYNTHETIC APERTURE RADAR FOR MAPPING OF FOREST DEGRADATION AND DEFORESTATION

A ONE-WEEK TRAINING ON SAR

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Lecture 3: Concepts and Benefits of Polarimetric SAR

UAF Alaska Satellite Facility
Making remote-sensing data accessible since 1991

UAF University of Alaska Fairbanks

NASA

Outline:

POLARIMETRIC SIGNALS

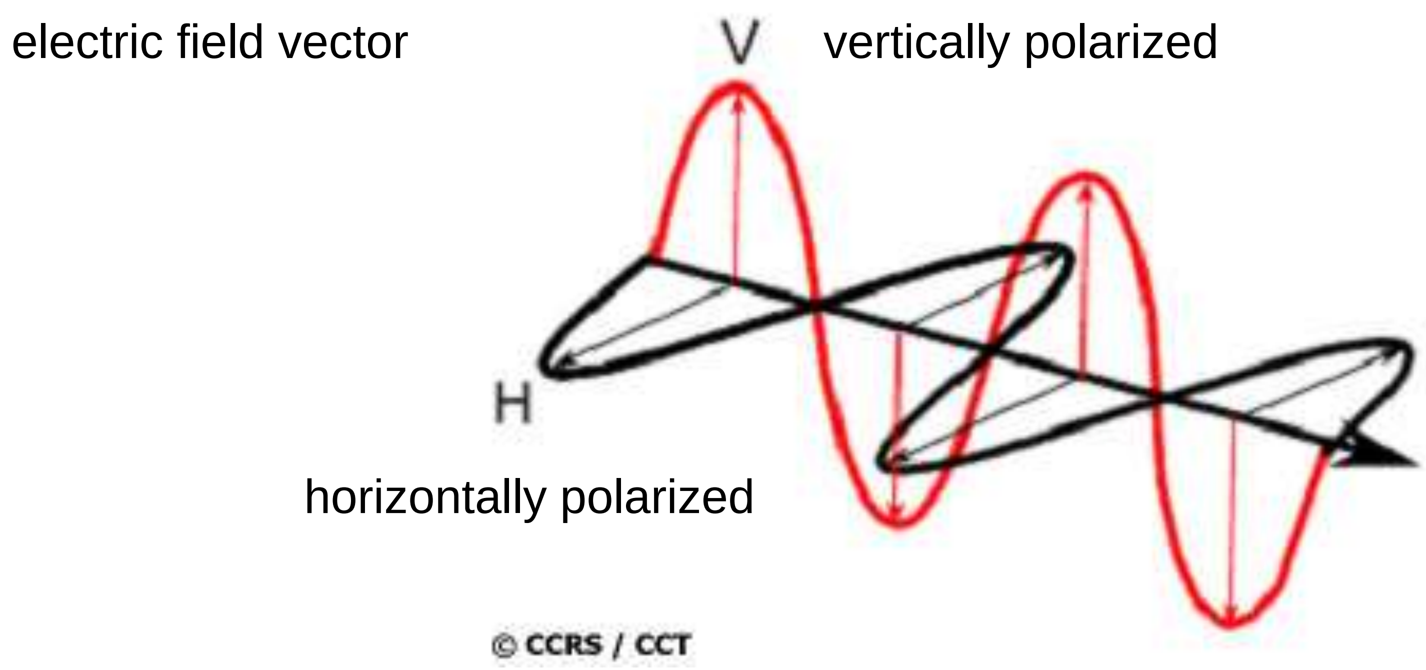
POLARIMETRIC SAR ACQUISITION

INTERPRETATION OF POLARIMETRIC DATA

HIGHER-LEVEL POLARIMETRIC TECHNIQUES

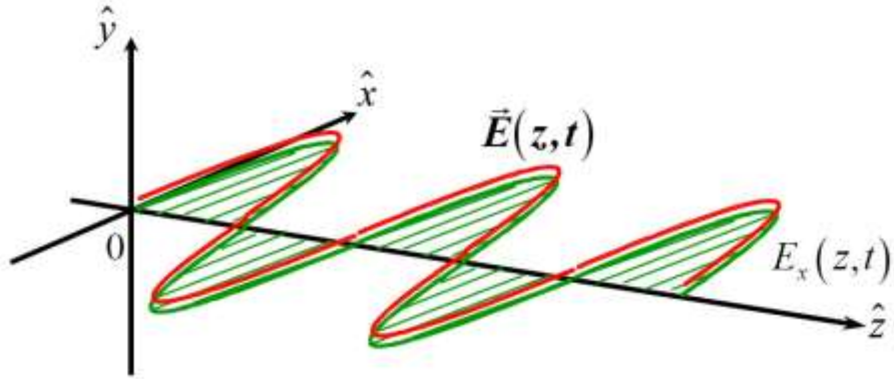
EXAMPLES OF SAR IMAGE CLASSIFICATION

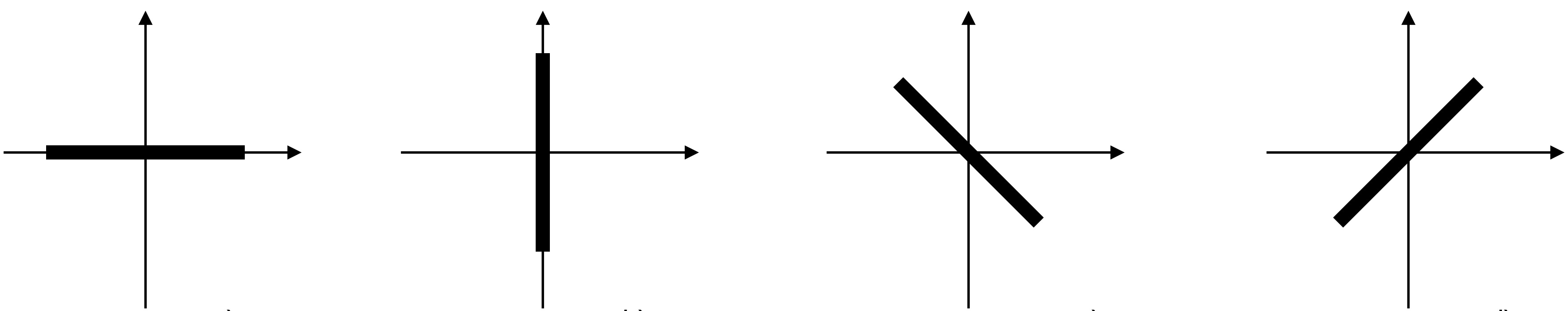
Polarization States of a Coherent Plane Wave



Linearly Polarized Signals

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

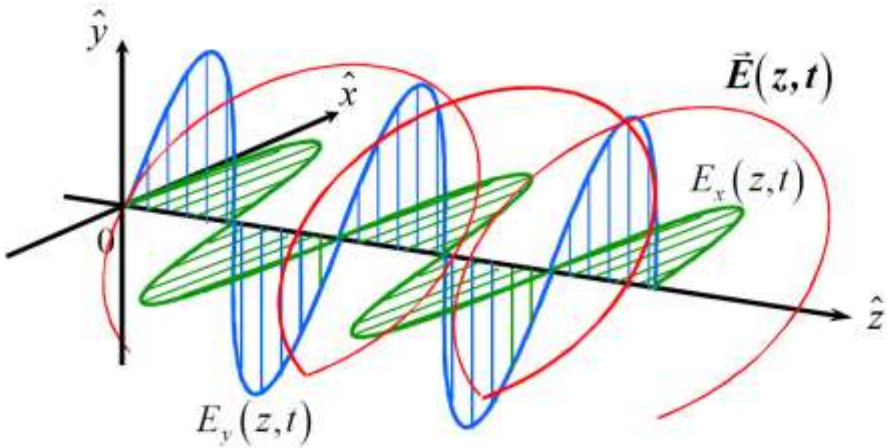


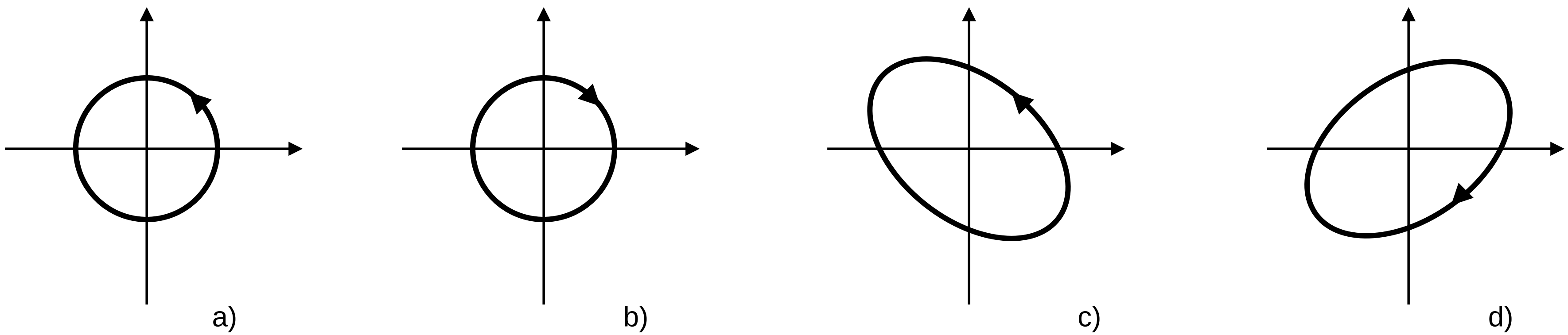


a) b) c) d)

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)





http://webphysics.davidson.edu/physlet_resources/dav_optics/examples/polarization.html

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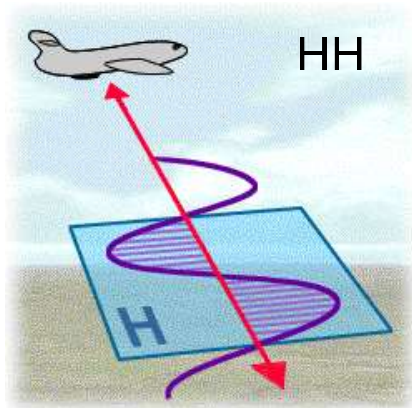
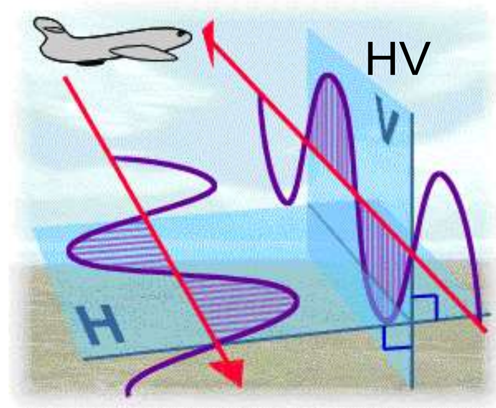
Polarization of SARs

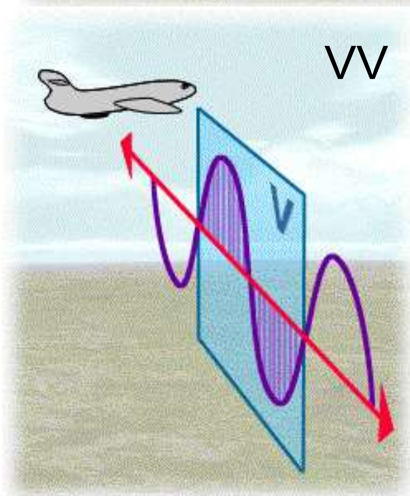
Horizontal Transmit
Horizontal Receive

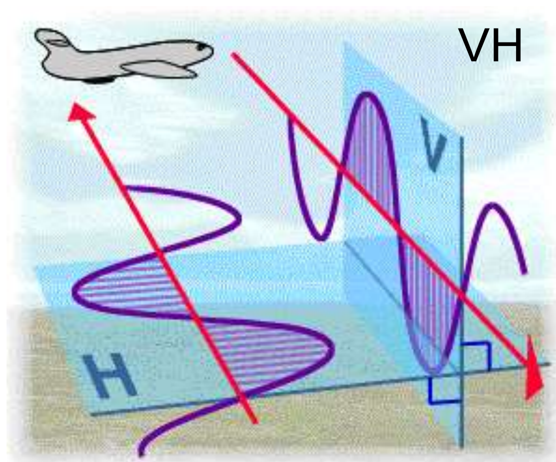




Horizontal Transmit
Vertical Receive

Vertical Transmit
Vertical Receive





Vertical Transmit
Horizontal Receive

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

Scattering Matrix

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:

$$[S] = \begin{pmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{pmatrix}$$ (scattering or Jones matrix)

For (monostatic) SARs: $S_{VH} = S_{HV}$ (reciprocity)

$$[S] = \begin{pmatrix} S_{HH} & S_{HV} \\ S_{HV} & S_{VV} \end{pmatrix}$$ (Sinclair matrix)

$\Rightarrow$ 3 independent amplitudes + 2 independent phases per pixel

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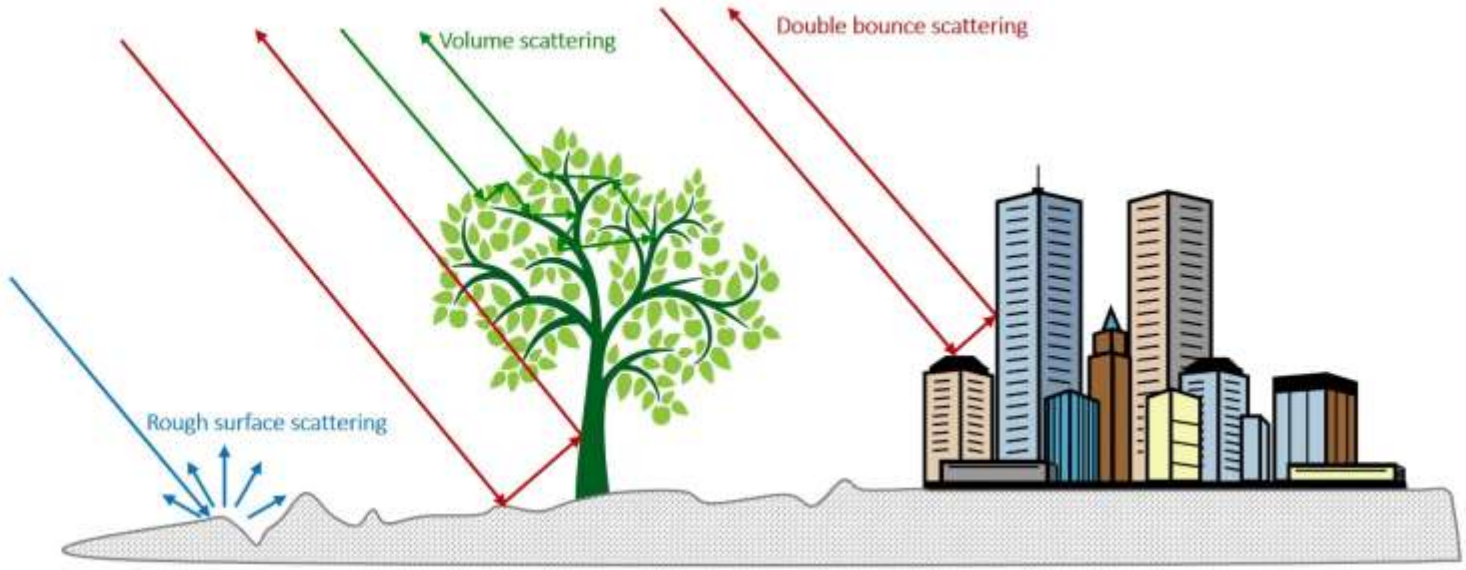
What Does SAR See?

- **At Radar wavelength, scattering is very 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, roads – Scattering strongly dependent on surface roughness and sensor wavelength (see Slide #36)
  - **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



Polarimetric Dependence of Scattering Principles

Relative scattering strength by polarization:

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

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

Visual Interpretation – Color Composites

© E. Pottier – L. Ferro-Famil (05/2009)

RGB Coding:

HH-VV

2HV

HH+VV

So-called "Pauli" decomposition

Information Extraction from Full-Polarimetric Data

- **If all four polarimetric channels (HH, HV, VH, VV) available:**
  - RGB Composits can be created
  - Automatic image classification in classes “Rough Surface”, “Vegetation”, and “Urban Structures” can be created

- **Polarimetric Decompositions Mathematically Challenging:**
  - While we will skip most of polarimetric theory, I am providing more detailed information in the slides for your review at a later time

- **I will provide you with a very brief overview and a pointer to software that can be used for polarimetric processing**

Sinclair Decomposition

A Simple Method for RGB Creation

- **Definition**:
  - $$\vec{s} = \begin{array}{cr} \begin{bmatrix} S_{HH} \\ S_{HV} + S_{VH} \\ S_{VV} \end{bmatrix} & \begin{array}{r} \text{Double bounce dominated} \\ \text{Volume dominated} \\ \text{Surface dominated} \end{array} \end{array}$$

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

The Pauli Scattering Vector

The Simplest of all Polarimetric Decompositions

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

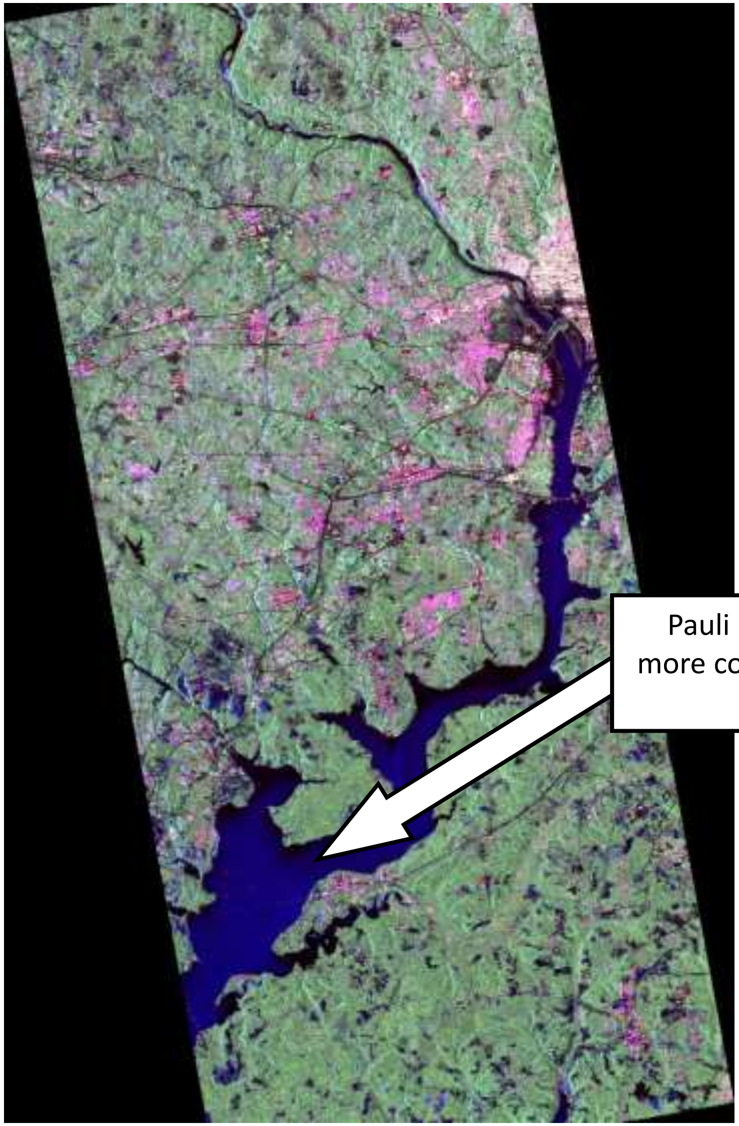
$$\underline{k} = \frac{1}{\sqrt{2}} \begin{bmatrix} S_{HH} + S_{VV} \\ S_{HH} - S_{VV} \\ 2S_{HV} \end{bmatrix} \begin{matrix} \text{Surface scattering} \\ \text{Double bounce scattering} \\ \text{Volume scattering} \end{matrix}$$

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

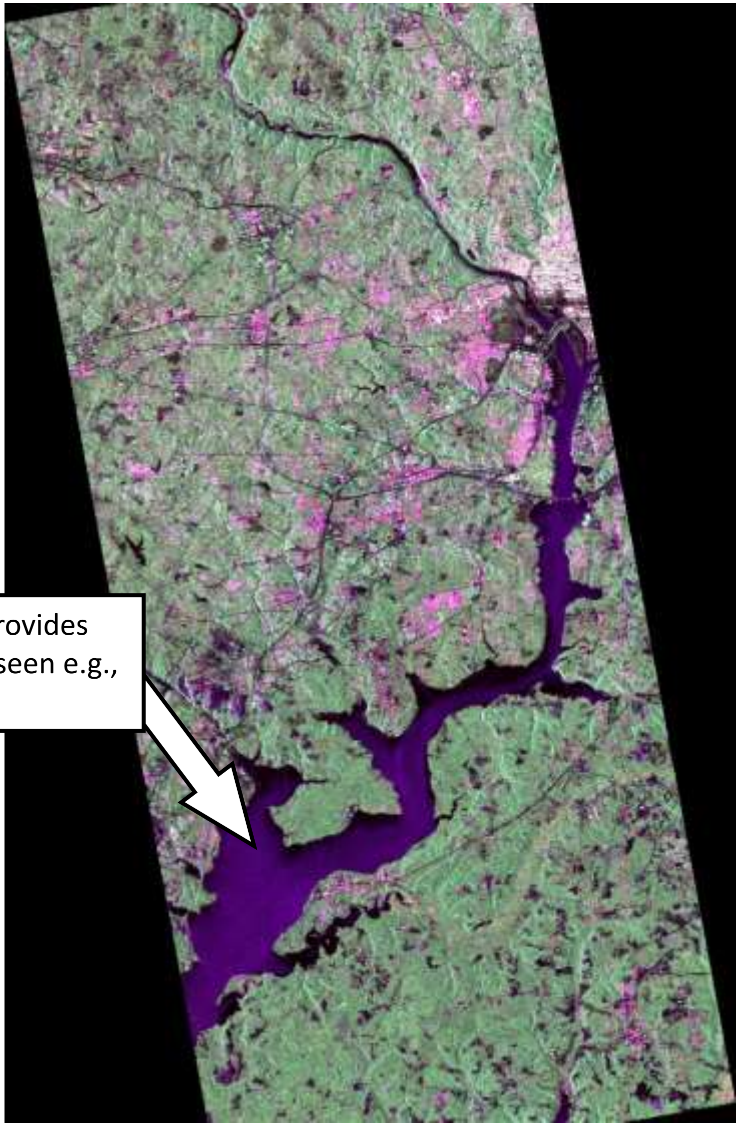
Pauli & Sinclair Decomposition

Washington, D.C., Example

Pauli decomposition (HH-VV, HV+VH, HH+VV)
(even bounce, volume, odd bounce)



Sinclair decomposition (HH, HV+VH, VV)
(*preferred* double bounce, volume, *preferred* surface)



Pauli Decomposition provides more correct "colors" as seen e.g., in water

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

- **Other Typical Decomposition Techniques include:**
  - Cholesky decomposition
  - Eigendecomposition
  - Singular Value Decomposition
  - Pauli Decomposition
  - …

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

Available Software Tools

- **PolSARPro is a freely available software tool provided by ESA**
- Can be downloaded at: https://earth.esa.int/web/polsarpro/home
- Includes all available polarimetric decomposition methods for dual-pol and quad-pol SAR data
- Output files of PolSARPro can be imported into MapReady for geocoding.
- In addition to the software also tutorials to Polarimetry can be downloaded

What To Do When Only Dual-Pol Data Are Available?

- **Full-polarimetric SAR data are rare and most modern SAR sensors only provide images in two polarizations**
  - E.g.: Sentinel-1 provides only the channels VV and VH

→ The previously-shown RBG images cannot be created (at least one channel missing)

- **There are still some benefits of dual-pol SAR data:**
  - The VH channel contains information on volume scattering → good indicator for vegetation
  - Dual-pol data can still be used to create RGB images (see next slide)

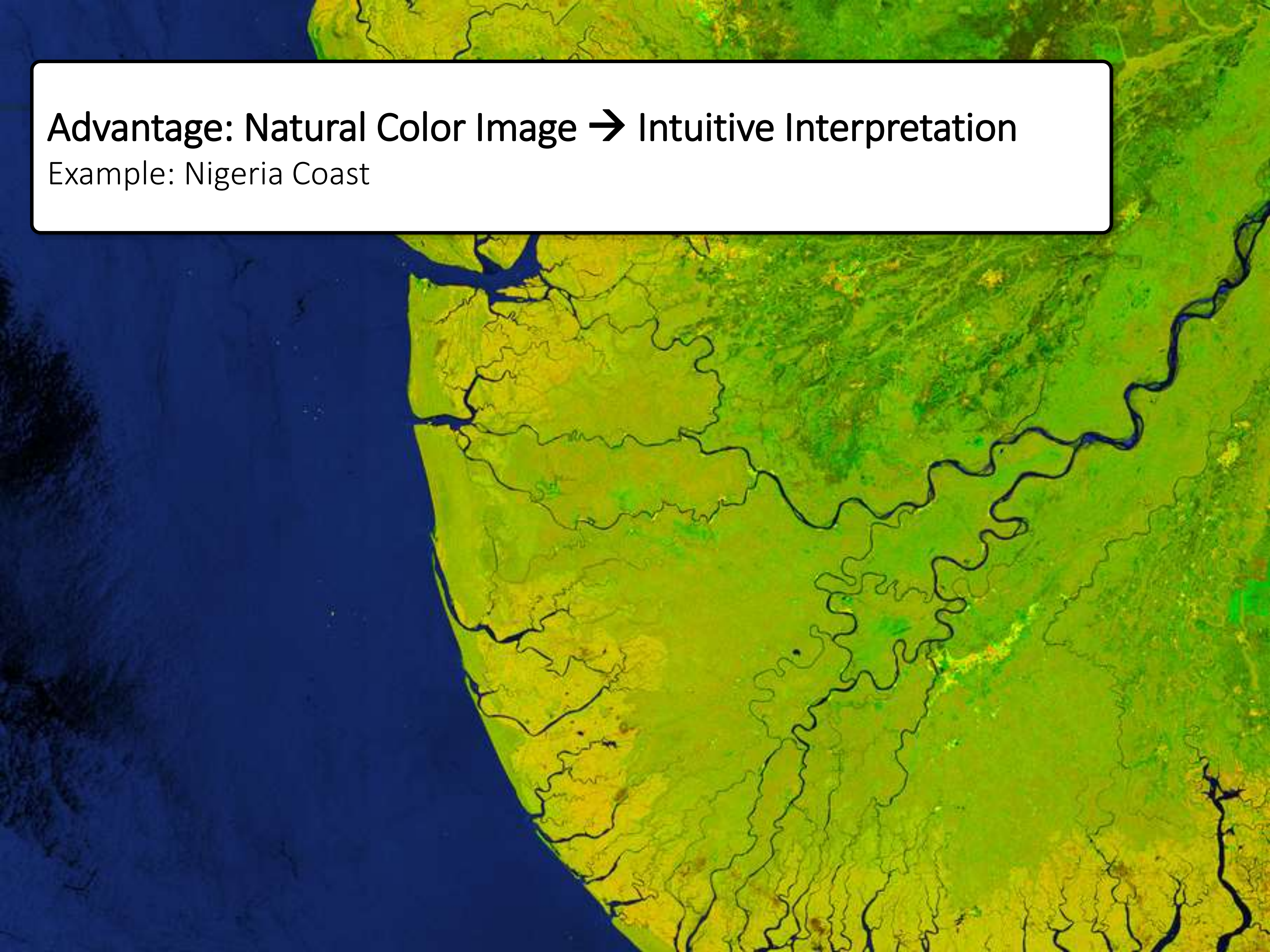
What To Do When Only Dual-Pol Data Are Available?

- **Dual-pol color image has the following channels:**
  - simple bounce (one dominant scattering signature; e.g., "pixel has only surface scattering) with no volume scattering — **Blue**
  - Simple bounce (polarized) with some volume scattering — **Red**
  - volume (depolarized) scattering — **Green**

Dual-pol RGB Image: Coast of Nigeria (near Warri)

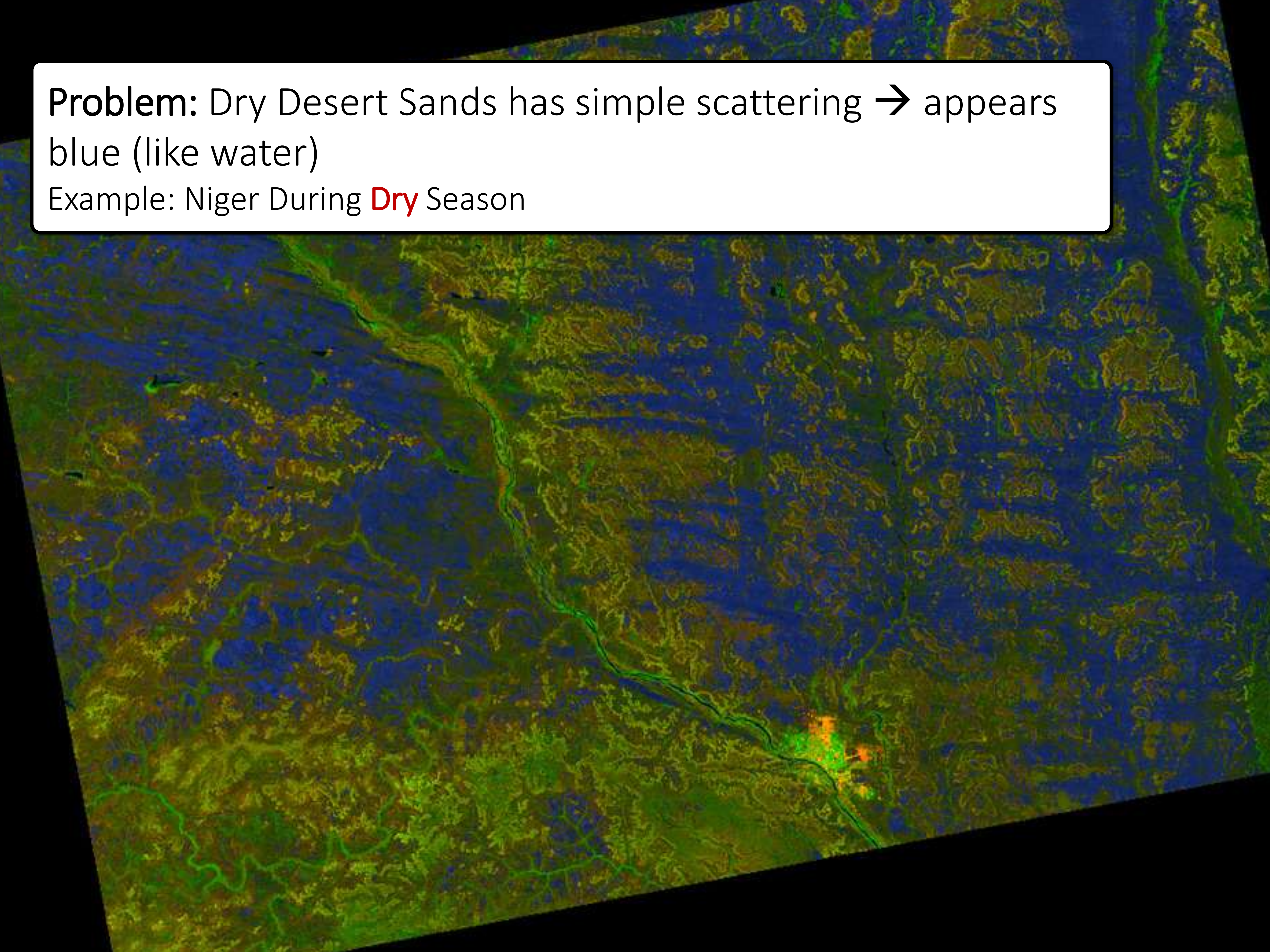
Advantage: Natural Color Image → Intuitive Interpretation

Example: Nigeria Coast



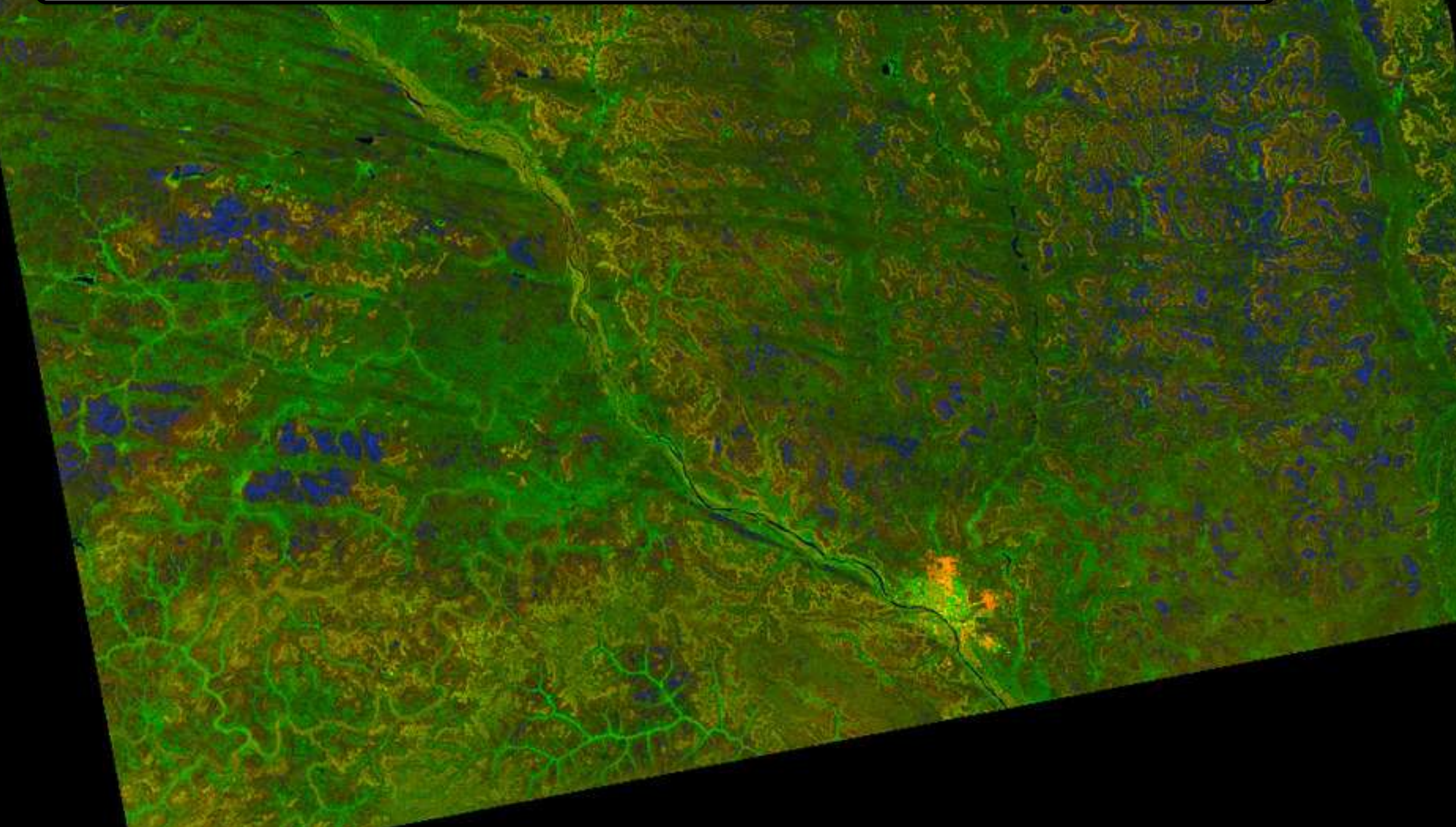
Problem: Dry Desert Sands has simple scattering → appears blue (like water)

Example: Niger During Dry Season



Problem: Dry Desert Sands has simple scattering → appears blue (like water)

Example: Niger During Wet Season → more natural looking



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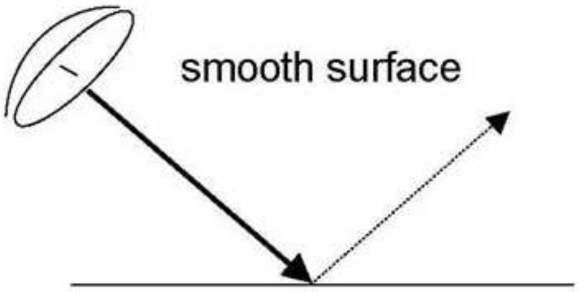
Scattering from Smooth Surfaces

Meaning of "Smooth":

irregularities of surface ≪ wavelength



Specular scattering

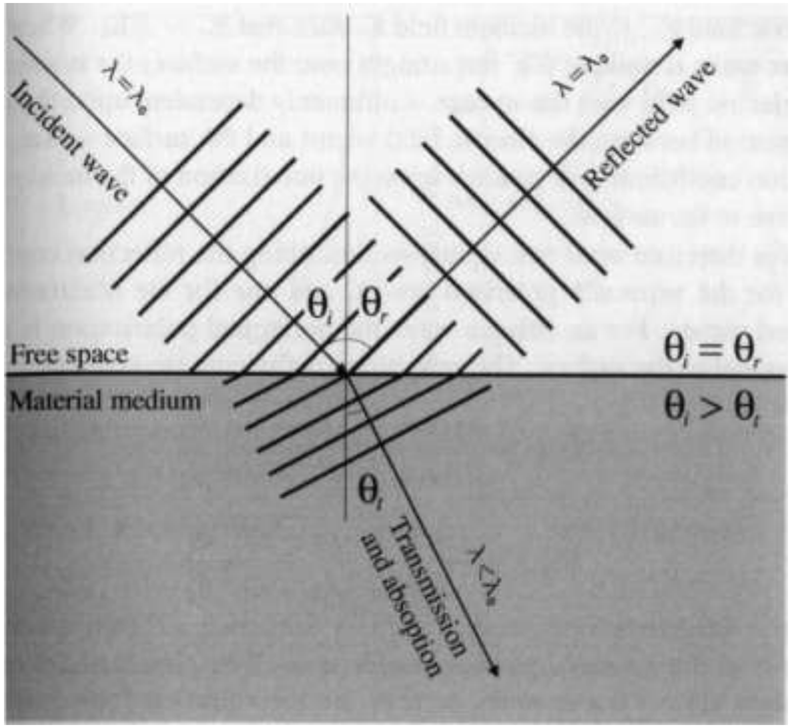
Scattering from Smooth Surfaces

- EM wave hitting interface at angle θ_i is partly scattered and partly transmitted
- For smooth surfaces, scattering forms coherent peak in specular direction

$$\theta_r = \theta_i$$

- Part of signal enters medium and is slowed down causing redirection (refraction) according to Snell's Law

$$\frac{sin\ \theta_i}{sin\ \theta_t} = \frac{n_2}{n_1}$$



From: Woodhouse (2006)

- Percentage of reflected energy is given by ***reflection coefficient*** R relating incident electric field E_i to reflected electric field E_r

$$E_r = R \cdot E_i$$

Quantifying the Surface Reflection Coefficient

- R depends on relative orientation between electric field vector and surface
- This means: R depends on the polarization of incident wave

- For linear polarization two equations are needed to describe R_{VV} (vertical to surface in transmit and receive) and R_{HH} (horizontal to surface)

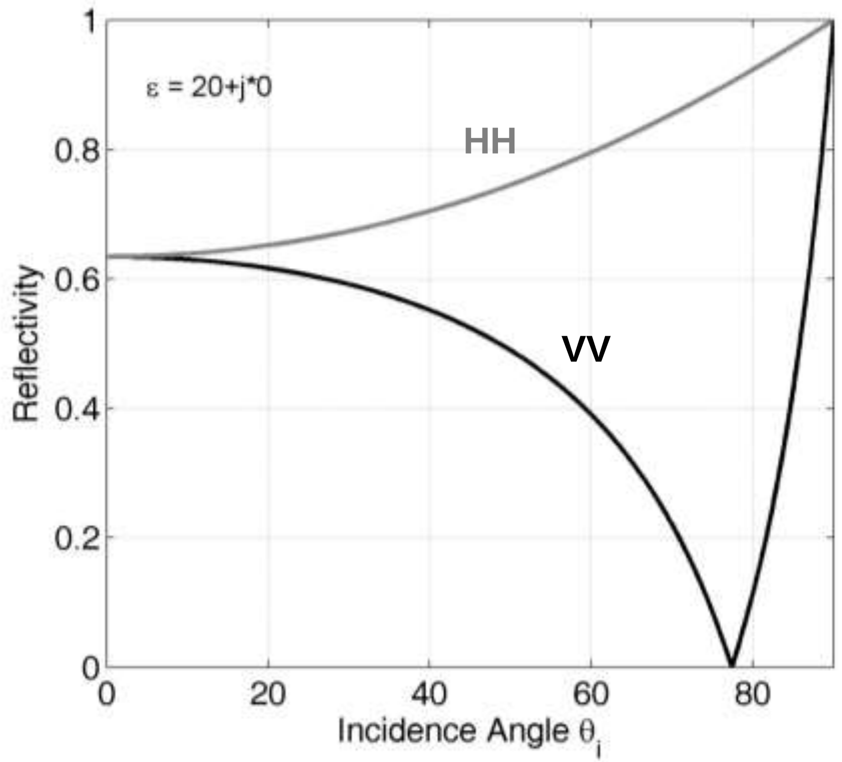
$$\boxed{\begin{aligned} R_{VV} &= \frac{\varepsilon \cdot cos\,\theta_i - \sqrt{\varepsilon - sin^2\,\theta_i}}{\varepsilon \cdot cos\,\theta_i + \sqrt{\varepsilon - sin^2\,\theta_i}} \\ R_{HH} &= \frac{cos\,\theta_i - \sqrt{\varepsilon - sin^2\,\theta_i}}{cos\,\theta_i + \sqrt{\varepsilon - sin^2\,\theta_i}} \\ R_{HV} = R_{VH} &= 0 \end{aligned}}$$

with ε being complex dielectric constant

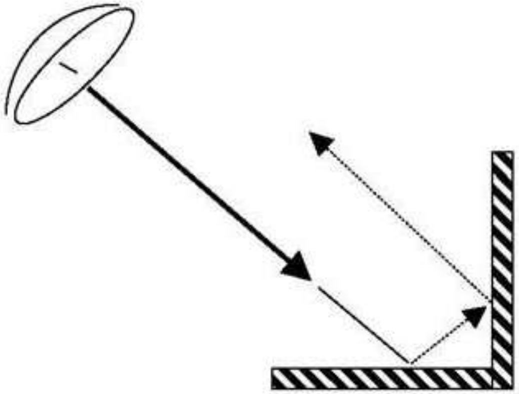
- **Fresnel reflection coefficients** R_{VV} and R_{HH}, defined between 0 and 1

Magnitude of Fresnel Reflection Coefficients

- One can see from both the Fresnel equations as well as the plot that $R_{VV} = R_{HH}$ if $\theta_i = 0^{\circ}$ and if $\theta_i = 90^{\circ}$
- R_{HH} is higher than R_{VV} $\rightarrow$ **surface backscatter stronger in horizontal polarization**



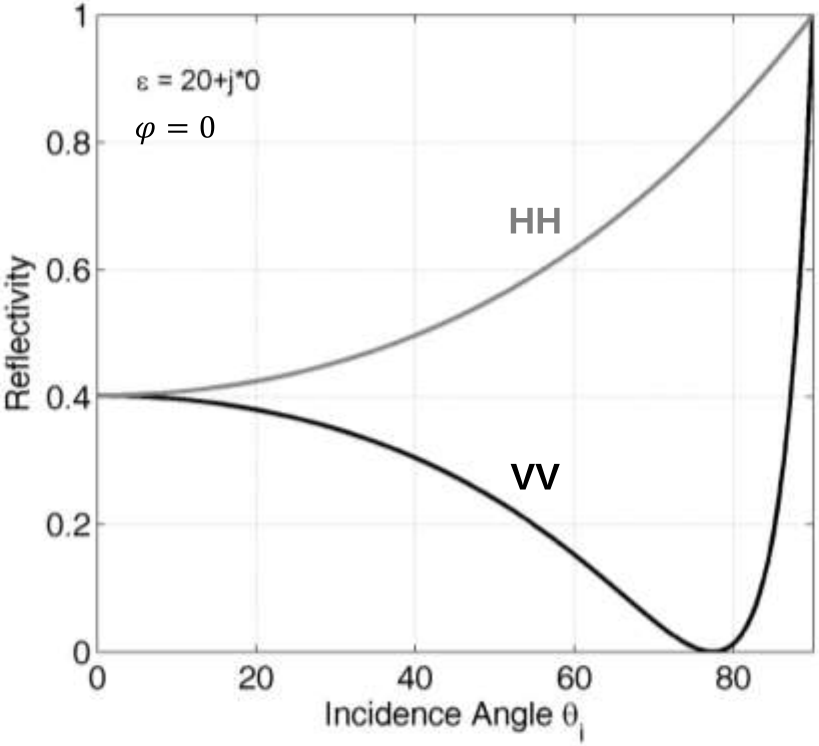
Scattering from Edges and Corners



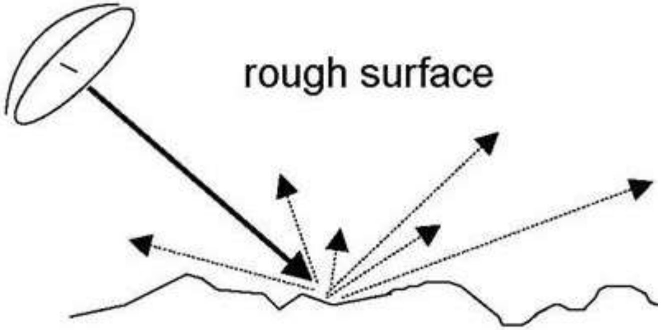
Scattering on Edges and Corners

- **If ε of both scattering surfaces is identical:**
  - **Scattering coefficient in HH**: $R_{HH} \cdot R_{HH}$
  - **Scattering coefficient in VV**: $R_{VV} \cdot R_{VV} exp(j\varphi)$ with R_{VV} from Slide 32 and φ being a potential material dependent phase shift relative to the HH signal

- Double-bounce scattering higher in horizontal (R_{HH}) than in vertical polarization (R_{VV})
- $R_{VH} = R_{HV} = 0$



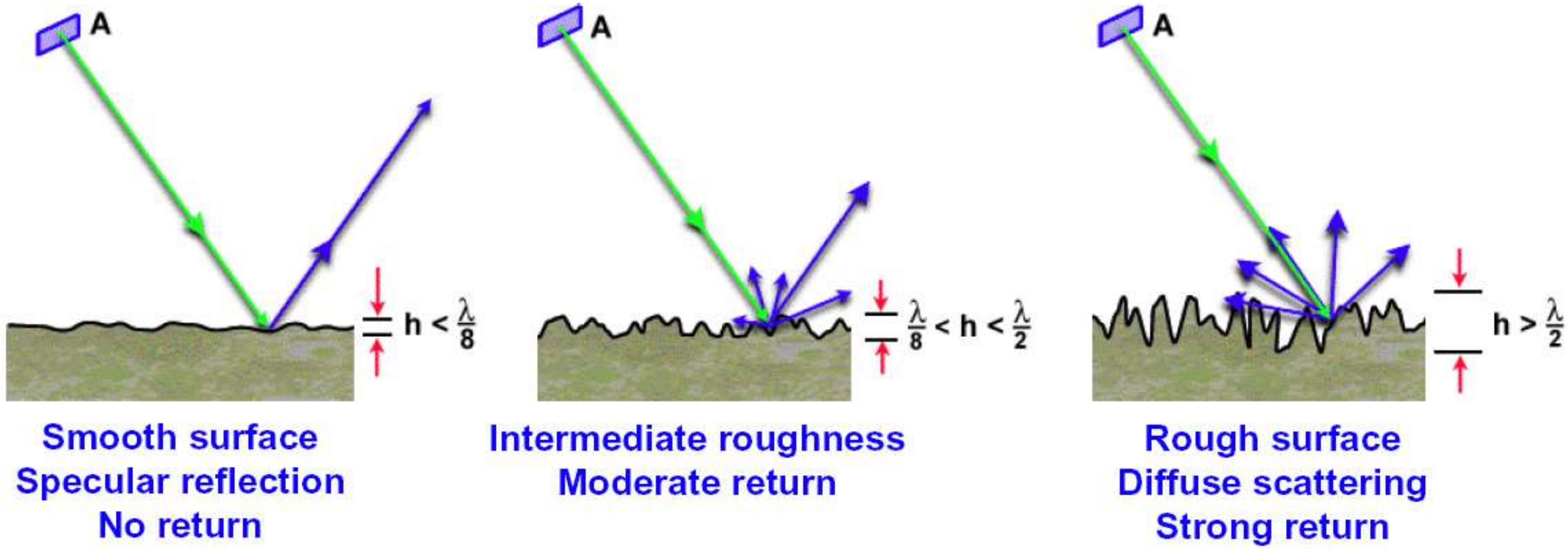
Scattering from Rough Surfaces



Meaning of "Rough":

irregularities of surface in the order of larger than wavelength

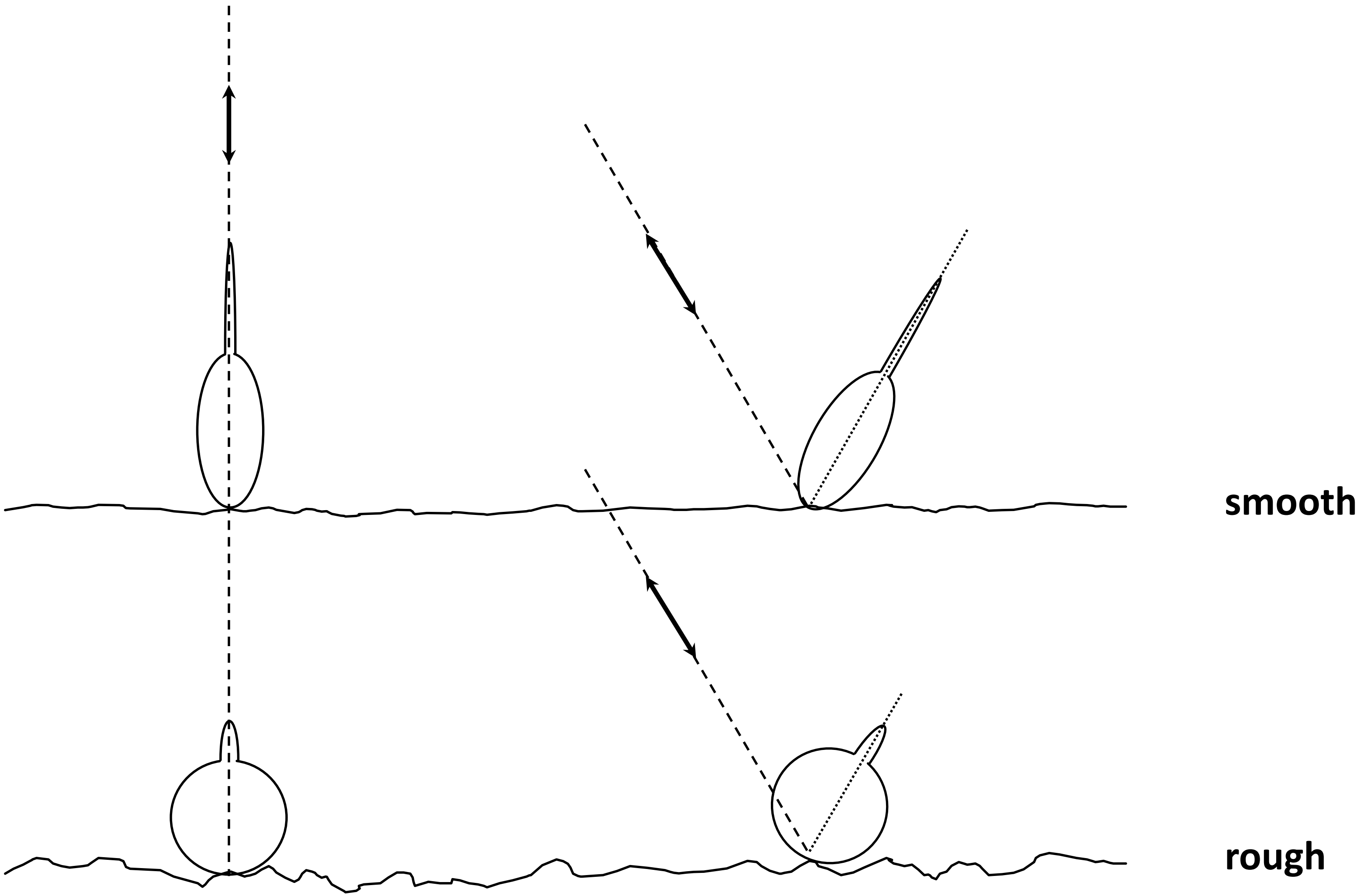
When is a Surface Rough? And how do Surfaces of Varying Roughness Scatter?



- Several criterion for roughness were developed that differ in strictness including the Fraunhofer criterion (a strict criterion) states:

$$h_{rough} > \frac{\lambda}{32 cos\theta_i}$$

Schematic Analysis of Incidence Angle Dependence of Scattering



Wavelength and Surface Roughness

$$\lambda = 2\,\text{cm} \ldots 25\,\text{cm}$$

rough

smooth

Scattering Processes: Bragg Scattering

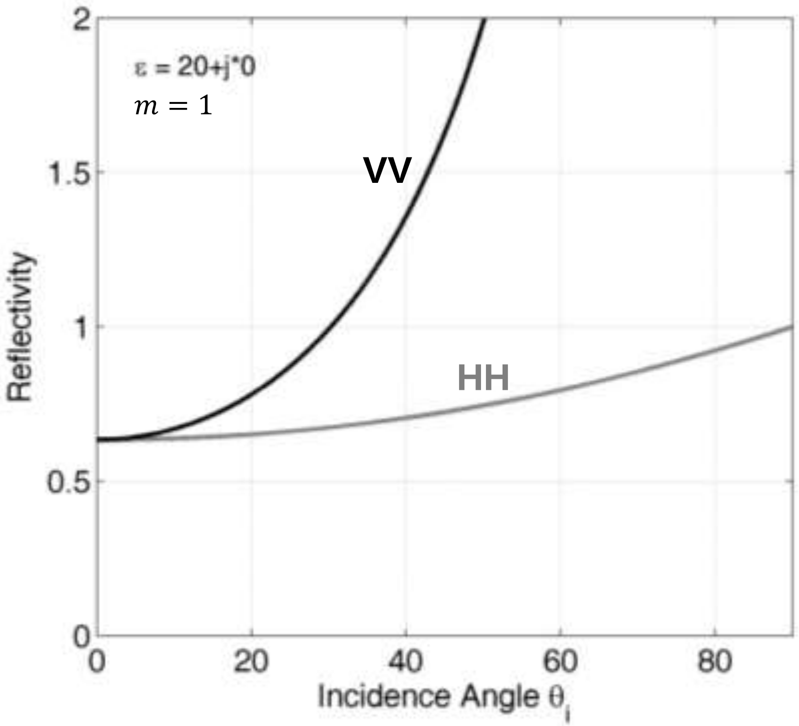
- **Polarimetric Dependence of Bragg scattering:**
  - **Horizontal polarization**:

$$R_{HH} = m \cdot \frac{cos\theta_i - \sqrt{\varepsilon_r - sin^2\theta_i}}{cos\theta_i + \sqrt{\varepsilon_r - sin^2\theta_i}}$$

  - **Vertical polarization**:

$$R_{VV} = m \cdot \frac{(\varepsilon_r - 1)\left[sin^2\theta_i - \varepsilon_r\left(1 + sin^2\theta_i\right)\right]}{\left(\varepsilon_r \cdot cos\theta_i + \sqrt{\varepsilon_r - sin^2\theta_i}\right)^2}$$

  - **Cross polarizations**:
    $R_{HV} = R_{VH} = 0$



… where ε is the dielectric constant of the surface and m depends on surface roughness

Polarimetric Dependence of Scattering Principles

<u>Relative scattering strength by polarization:</u>

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

Sinclair Decomposition

- **Definition**:
  - $\vec{s} = \begin{bmatrix} S_{HH} \\ S_{HV} + S_{VH} \\ S_{VV} \end{bmatrix} \begin{array}{l} \text{Double bounce dominated} \\ \text{Volume dominated} \\ \text{Surface dominated} \end{array}$

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

Different Ways Of Representing Polarimetric Data

- **Commonly used polarimetric target descriptors include:**

  - **[S]** Sinclair matrix
  - **<u>k</u>** Pauli Scattering Vector

  - **[K]** Kennaugh Matrix
  - **[T]** Coherency Matrix
  - **[C]** Covariance Matrix

  Will not be discussed here

- 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" Ψ_P resulting in the Pauli vector $\underline{k}$

$$\underline{k} = \frac{1}{2} trace([S][\Psi_P])$$

where

$$[\Psi_P] = \left\{ \sqrt{2}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \sqrt{2}\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}, \sqrt{2}\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, \sqrt{2}\begin{bmatrix} 0 & -j \\ j & 0 \end{bmatrix} \right\}$$

- Resulting in:

$$\underline{k} = \frac{1}{\sqrt{2}} \begin{bmatrix} S_{HH} + S_{VV} & S_{HH} - S_{VV} & S_{HV} + S_{VH} & j(S_{HV} - S_{VH}) \end{bmatrix}^T$$

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:**

$$\underline{k} = \frac{1}{\sqrt{2}}\begin{bmatrix} S_{HH} + S_{VV} \\ S_{HH} - S_{VV} \\ 2S_{HV} \end{bmatrix}$$

Surface scattering

Double bounce scattering

Volume scattering

- 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
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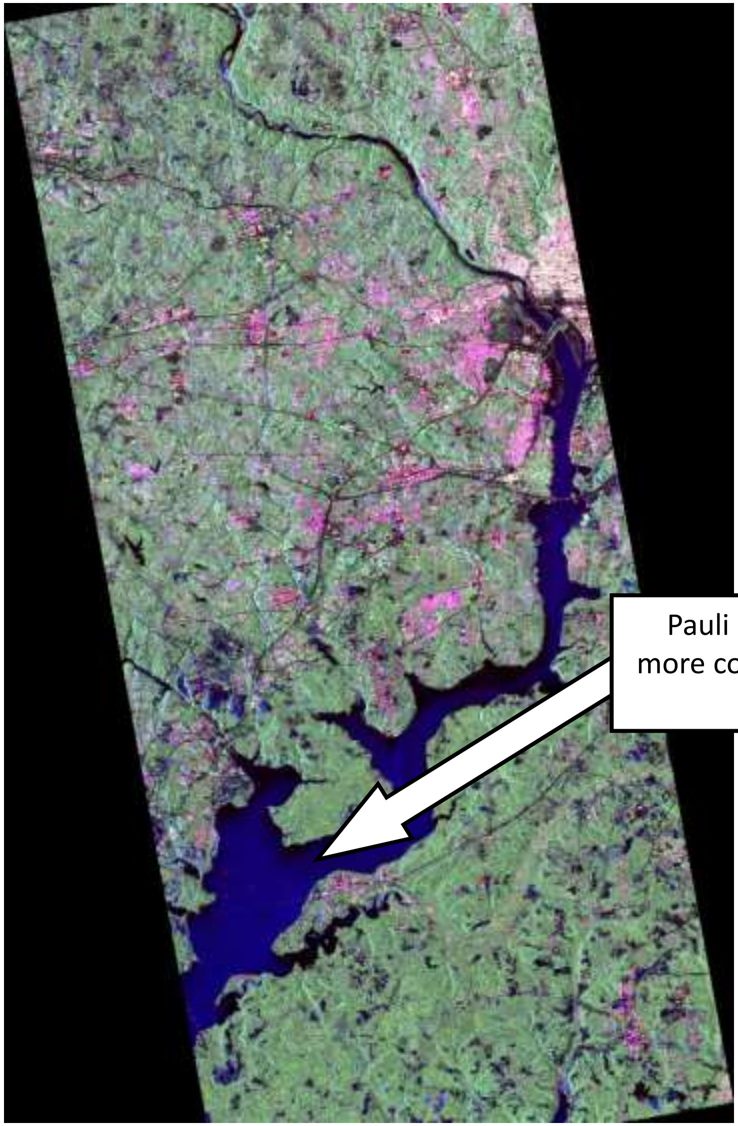
  - Pauli Decomposition
  - …

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

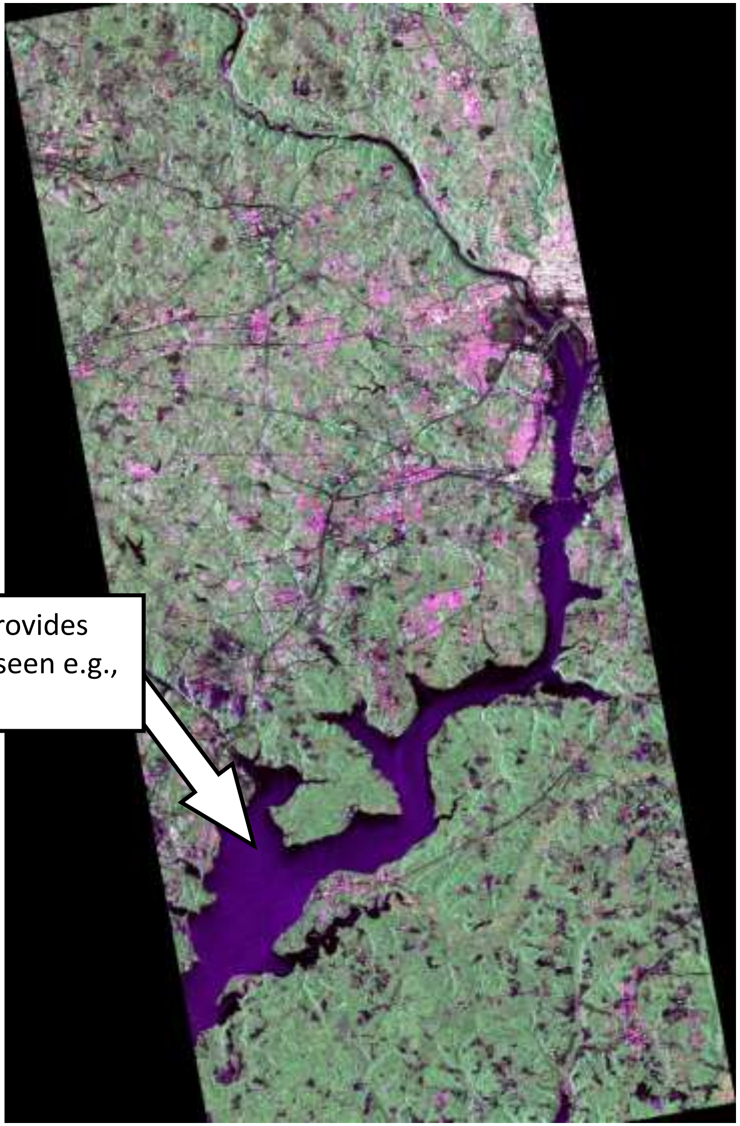
Pauli & Sinclair Decomposition

Washington, D.C., Example

Pauli decomposition (HH-VV, HV+VH, HH+VV)
(even bounce, volume, odd bounce)



Sinclair decomposition (HH, HV+VH, VV)
(*preferred* double bounce, volume, *preferred* surface)



Pauli Decomposition provides more correct "colors" as seen e.g., in water

Scene Classification based on Polarimetric Decompositions

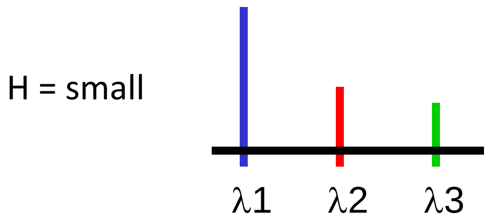
- **Unsupervised classifiers have been introduced in the recent years**
  - Based on physical properties of target and dominant scattering mechanism and NOT on dataset
    → No prior knowledge about scene content or terrain classes necessary

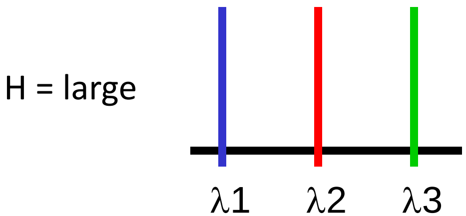
- **Main decomposition-based classifiers:**
  - Van Zyl: “odd bounce,” “even bounce,” “diffuse”
  - Freeman: Three component scattering model based classification
  - Cloude & Pottier: H / α Classifier
  - Cloude & Pottier: H / A / α Classifier
  - Yamaguchi: Four Component scattering model based classification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

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

The Unsupervised H / α 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) $\bar{\alpha}$ Angle** [calculated from Eigenvector]: Indicative of dominant scattering mechanism
    - If $\bar{\alpha} \approx 0^{\circ}$ → surface scattering
    - If $\bar{\alpha} \approx 45^{\circ}$ → volume scattering
    - If $\bar{\alpha} \approx 90^{\circ}$ → dihedral or multiple scattering

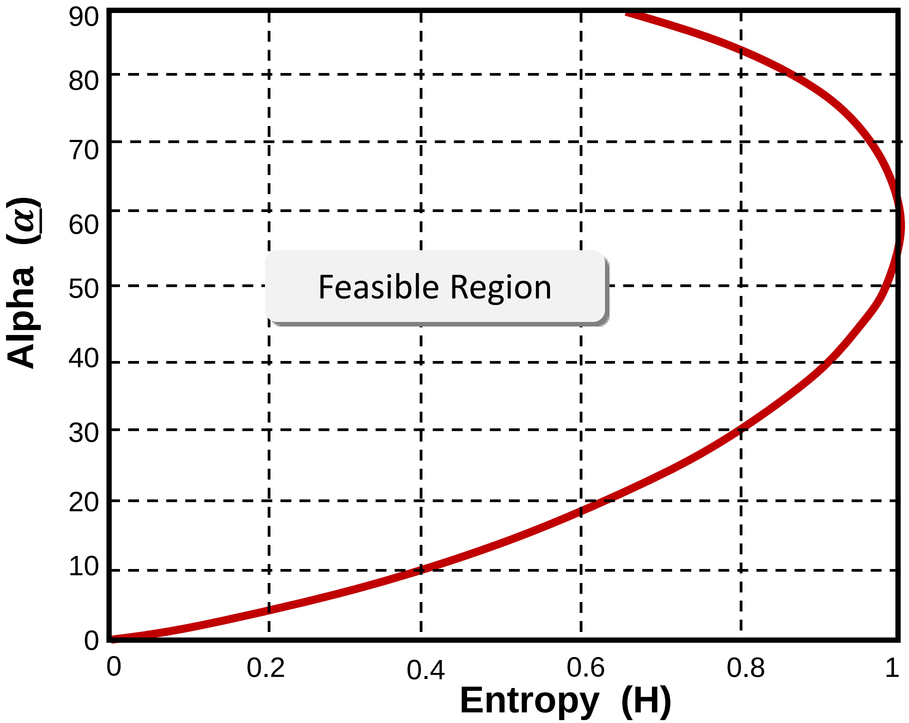
$$\bar{\alpha} = \sum_{i=1}^{3} \alpha_i P_i$$

with $P_i = \frac{\lambda_i}{\lambda_1+\lambda_2+\lambda_3}$

and α_i = angle relative to vertical

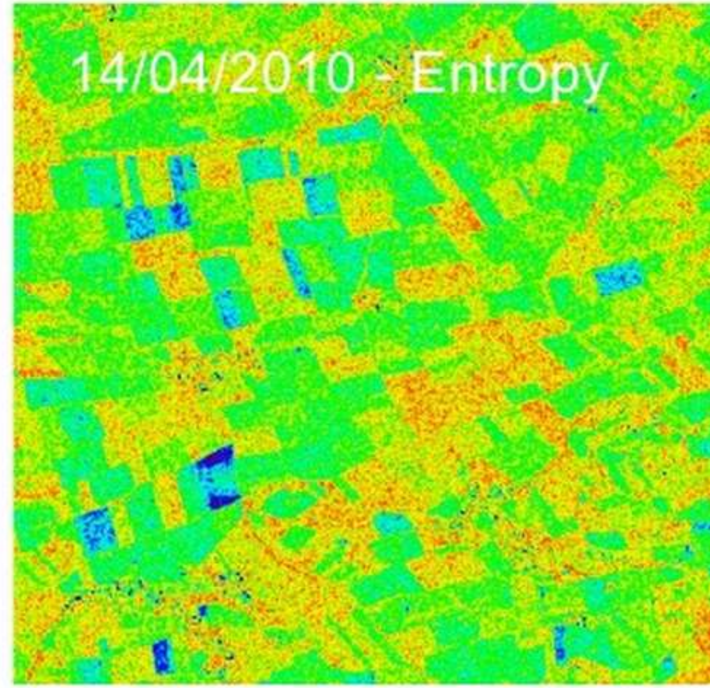
The Unsupervised H / α Classifier

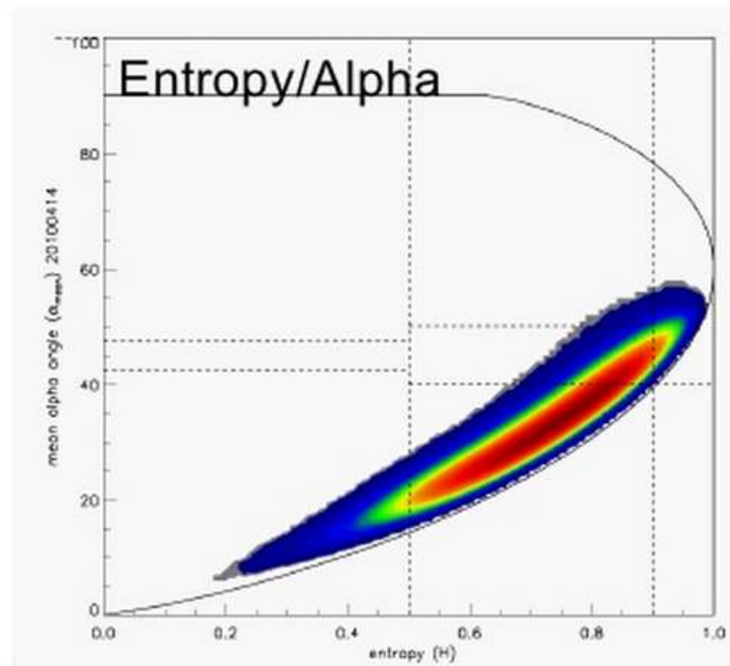
- **The H/α diagram is shown below**
- By definition, all image pixels will have H/α values within the feasible region



Example of SAR Data in H/α Diagram

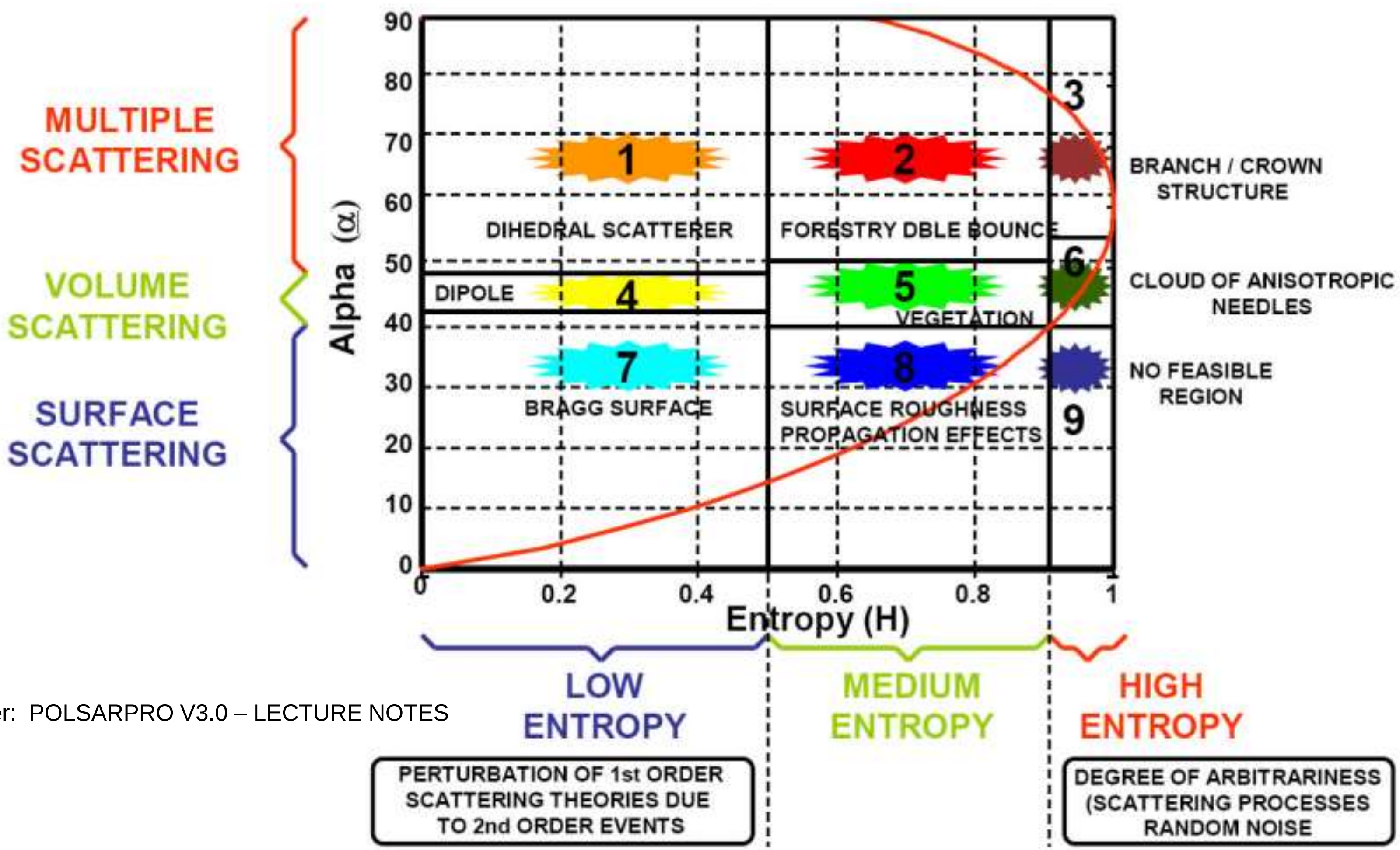
- **TerraSAR-X SAR Data**
- **Agricultural Fields are shown**
- **Data Characteristics:**
  - Spread across a range of H values with average on $H \approx 0.8$
  - Low α indicates dominance of surface scattering
  - Indication of various density of crops on fields





The Unsupervised H / α Classifier

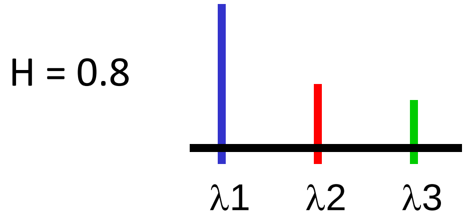
- **The H/α plane is partitioned into nine classes**
- Classes are chose on general properties of scattering

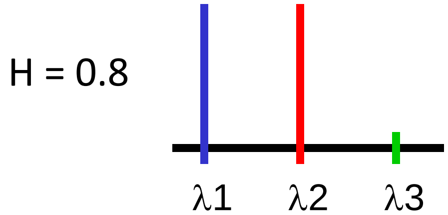


W. Boerner: POLSARPRO V3.0 – LECTURE NOTES

Refinement: The Unsupervised H / A / α (Entropy/Anisotrophy/Alpha) Classifier

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





- **Anisotrophy** was introduced to solve these problems by distinguishing cases where l2 ≈ l3 from cases where l2 is large and l3 is small

$$A = \frac{\lambda_2 - \lambda_3}{\lambda_2 + \lambda_3}$$

⇨ Complementary to Entropy H
⇨ Additional discrimination when H > 0.7

Available Software Tools

- **PolSARPro is a freely available software tool provided by ESA**
- Can be downloaded at: https://earth.esa.int/web/polsarpro/home
- Includes all available polarimetric decomposition methods for dual-pol and quad-pol SAR data
- Output files of PolSARPro can be imported into MapReady for geocoding.
- In addition to the software also tutorials to Polarimetry can be downloaded

Outline:

POLARIMETRIC SIGNALS

POLARIMETRIC SAR ACQUISITION

INTERPRETATION OF POLARIMETRIC DATA

EXAMPLES OF SAR IMAGE CLASSIFICATION

The H / α Classifier

Example Natural Environment

- **Mixed natural environment in Germany**

Optical image

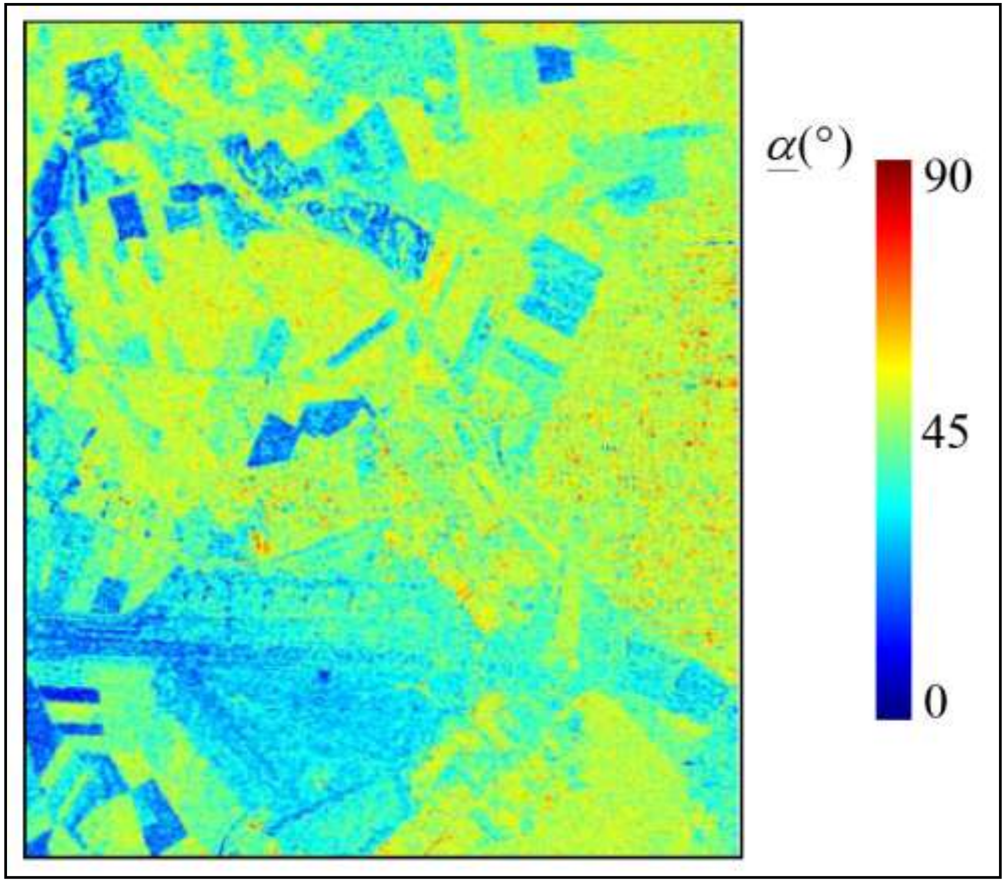
Polarimetric SAR color composite

The H / α Classifier

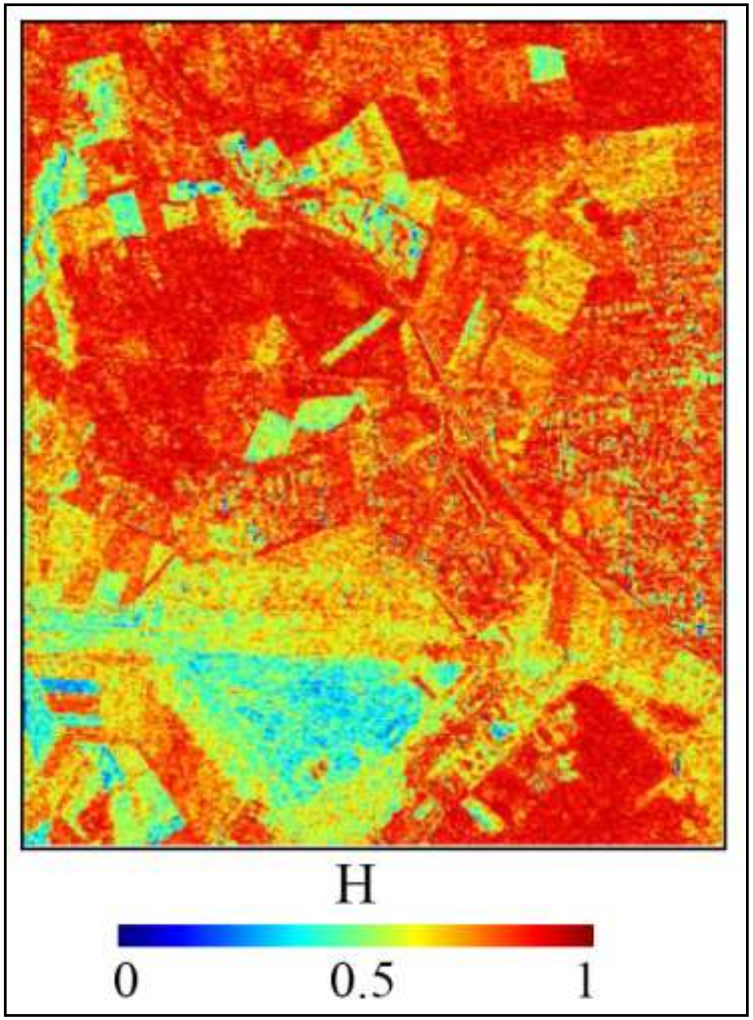
Example Natural Environment

- **Mixed natural environment in Germany**

***α* angle**



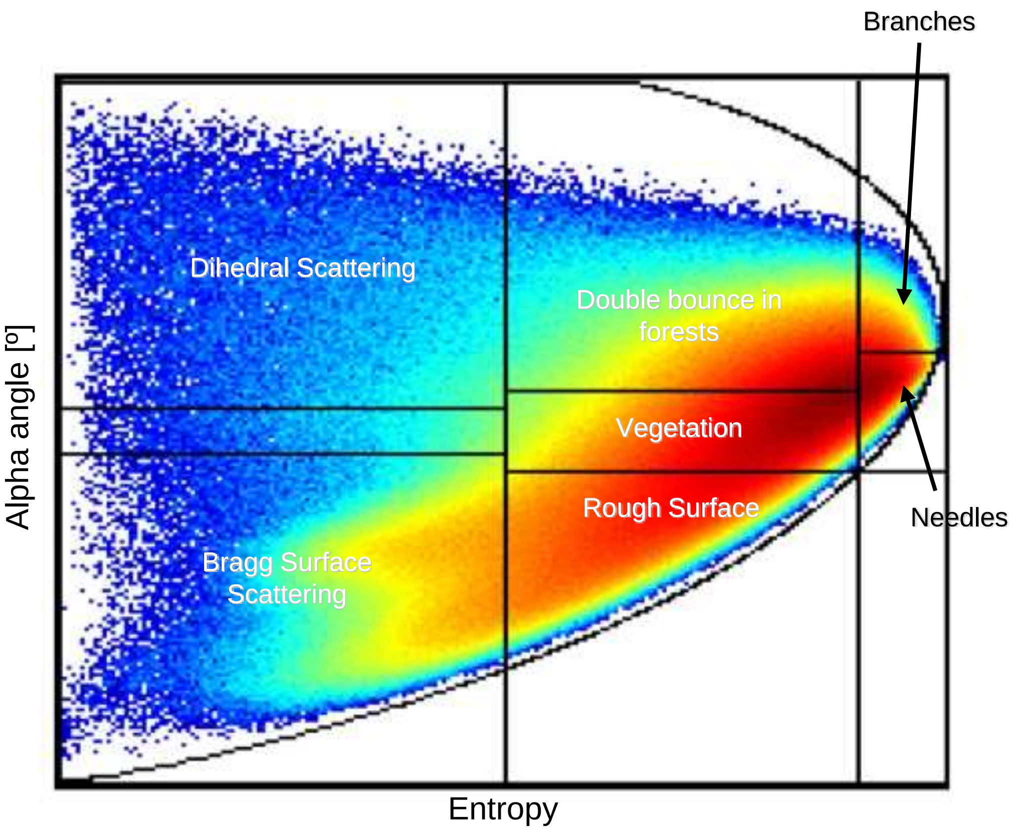
Entropy



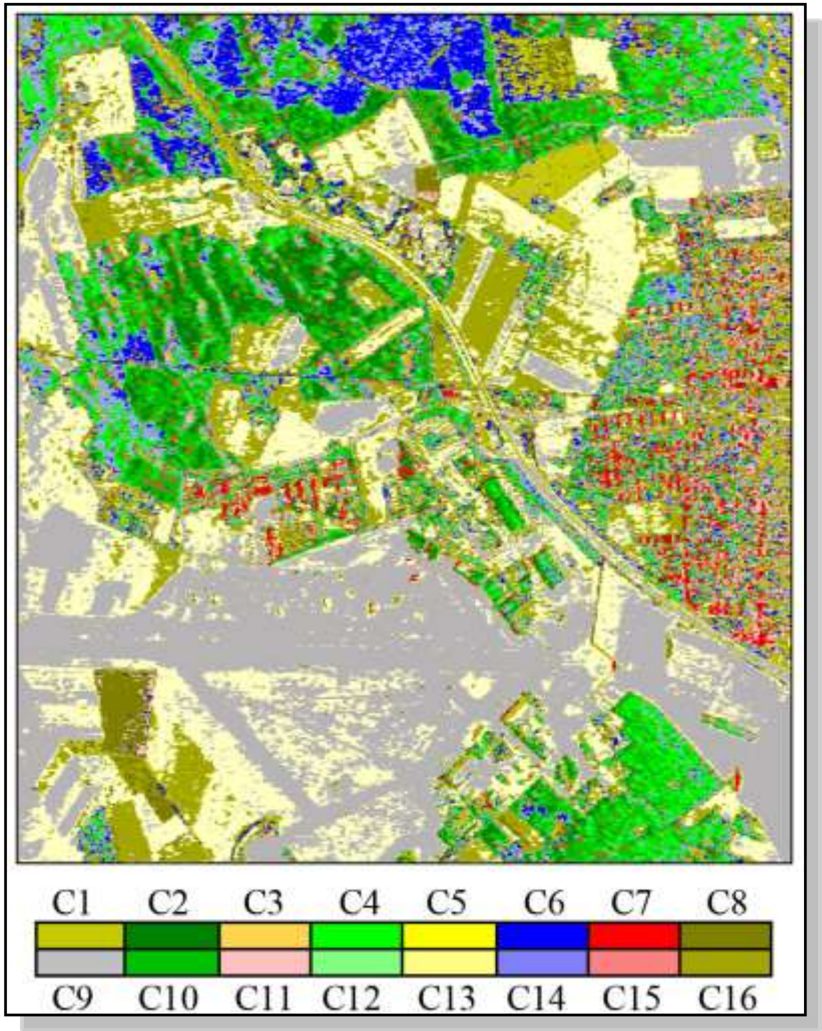
Courtesy: I. Hajnsek/DLR

The H / α Classifier

Example Natural Environment



Segmentation Result

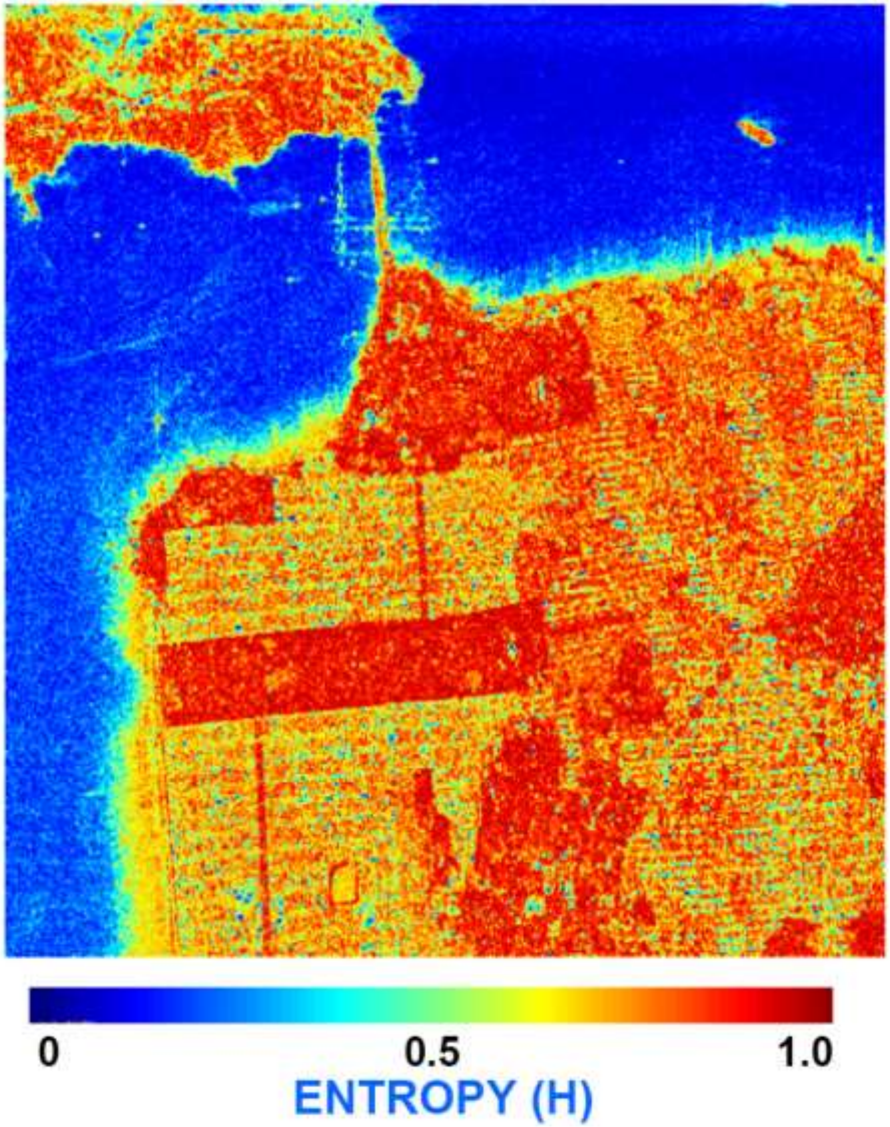


Courtesy: I. Hajnsek/DLR

The H / α Classifier

Example: San Francisco Bay Area

Pauli representation

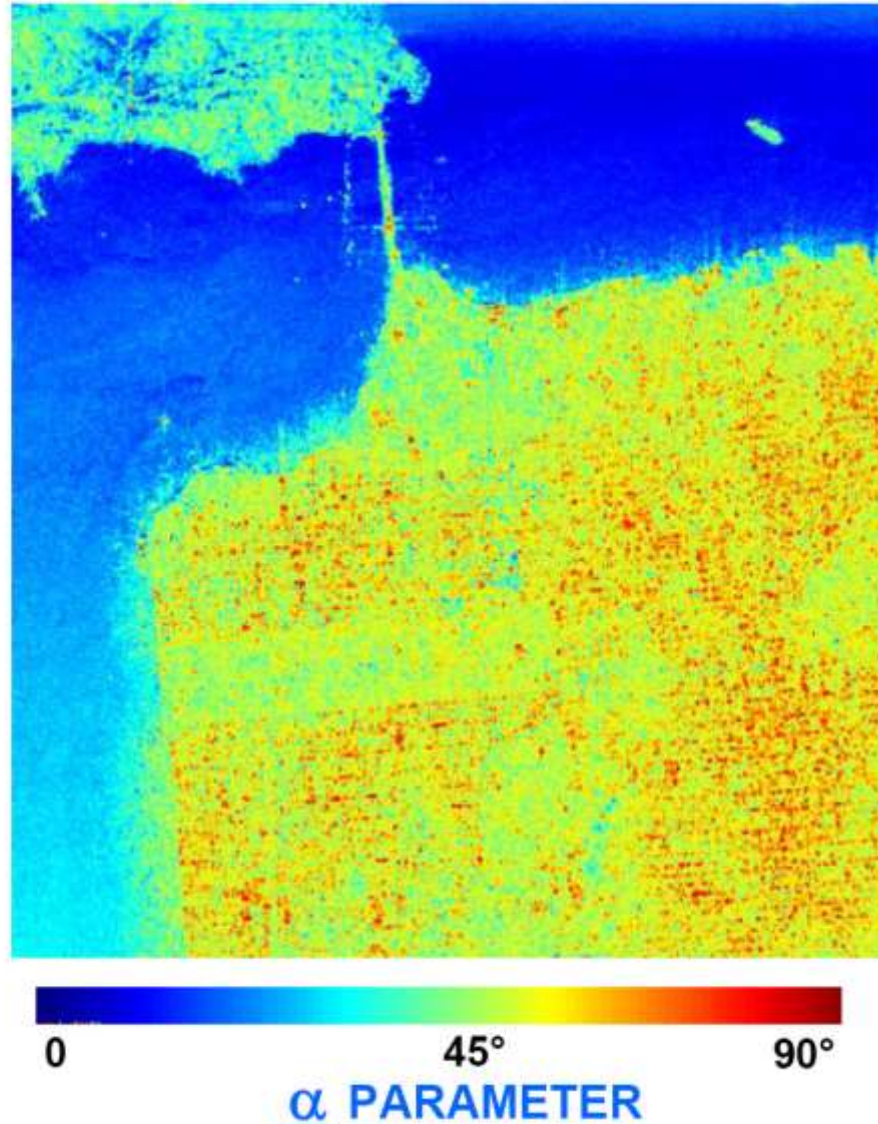


The H / α Classifier

Example: San Francisco Bay Area

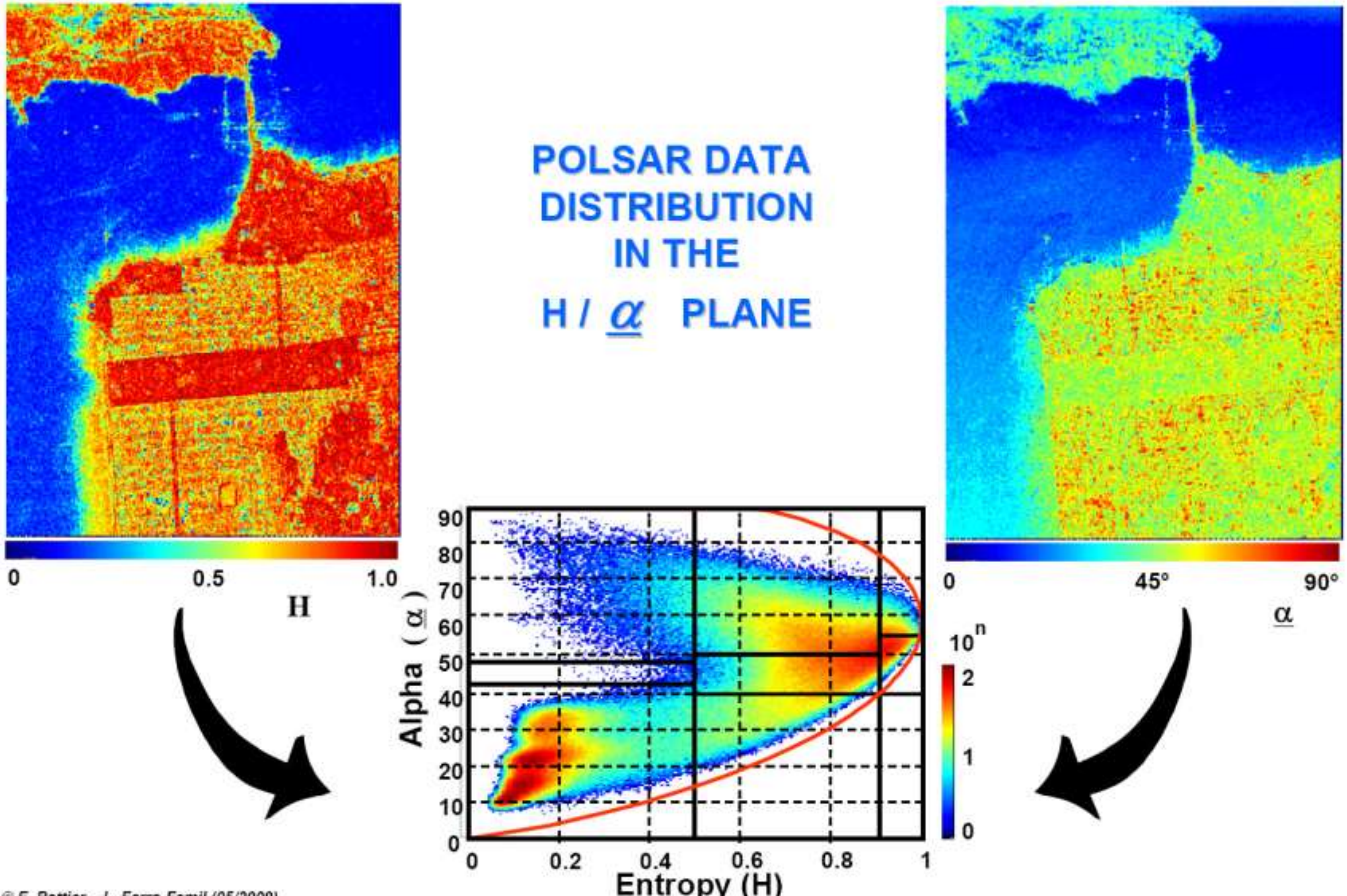
© E. Pottier – L. Ferro-Famil (05/2009)

Pauli representation



The H / α Classifier

Example: San Francisco Bay Area



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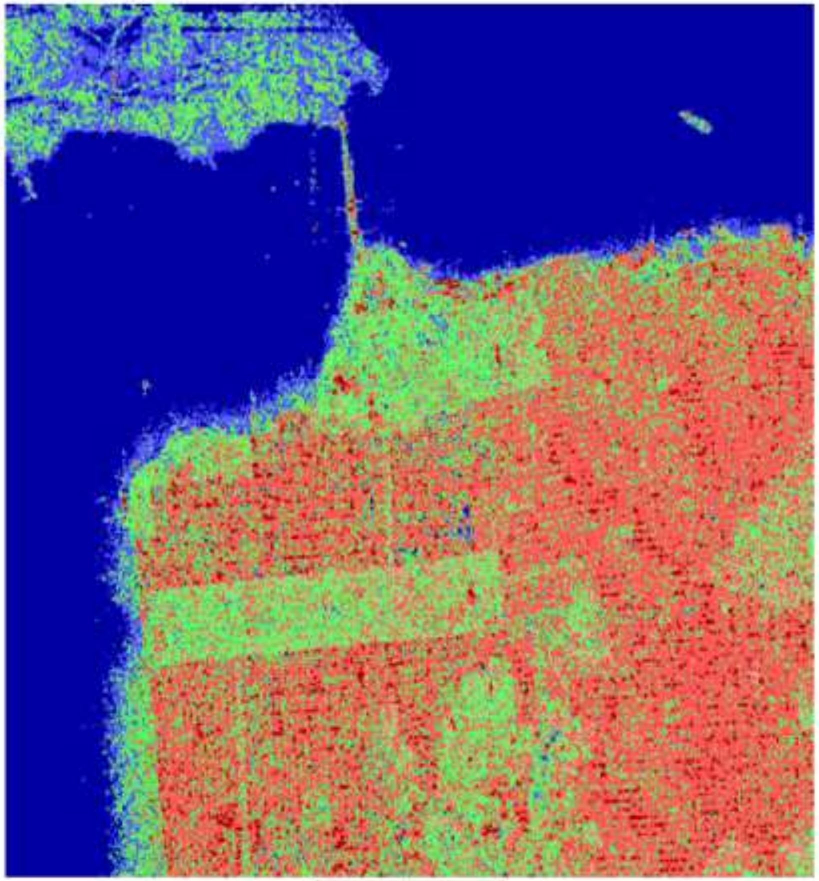
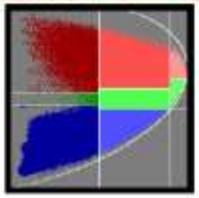
The H / α Classifier

Example: San Francisco Bay Area

Pauli representation

H - α classification





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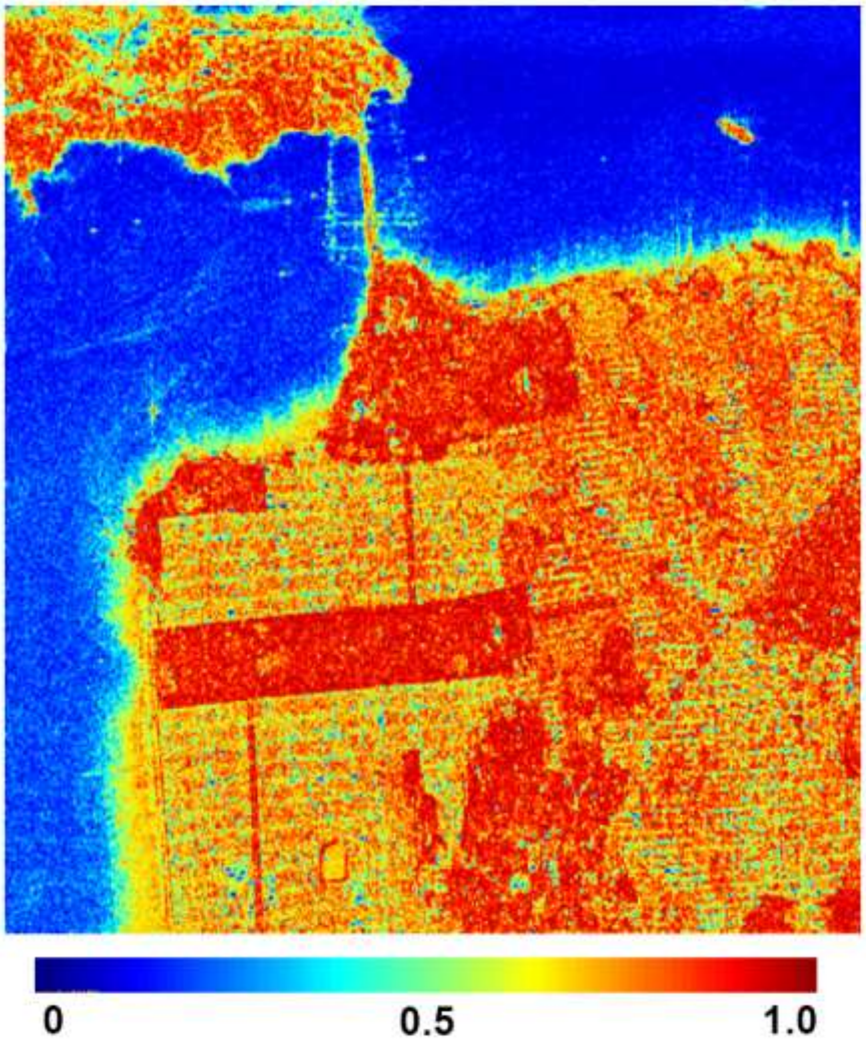
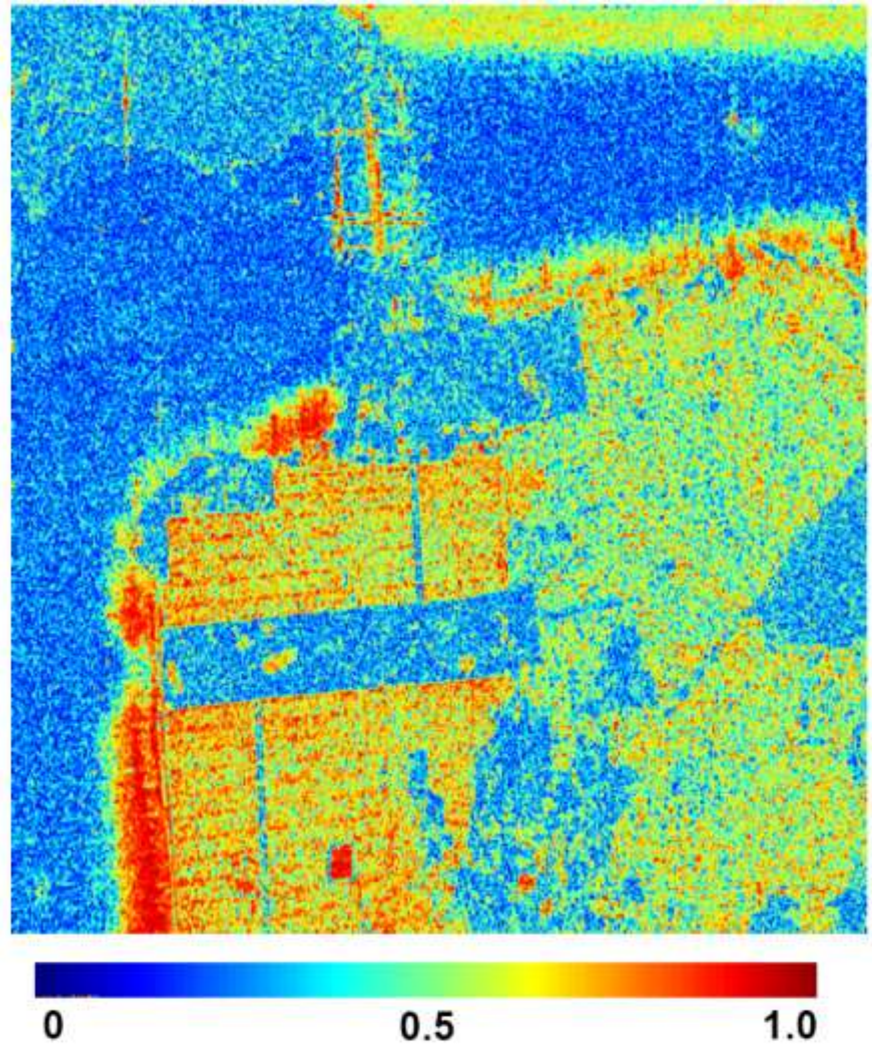
The H / A / α Classifier

Example: San Francisco Bay Area



ENTROPY (H)



ANISOTROPY (A)

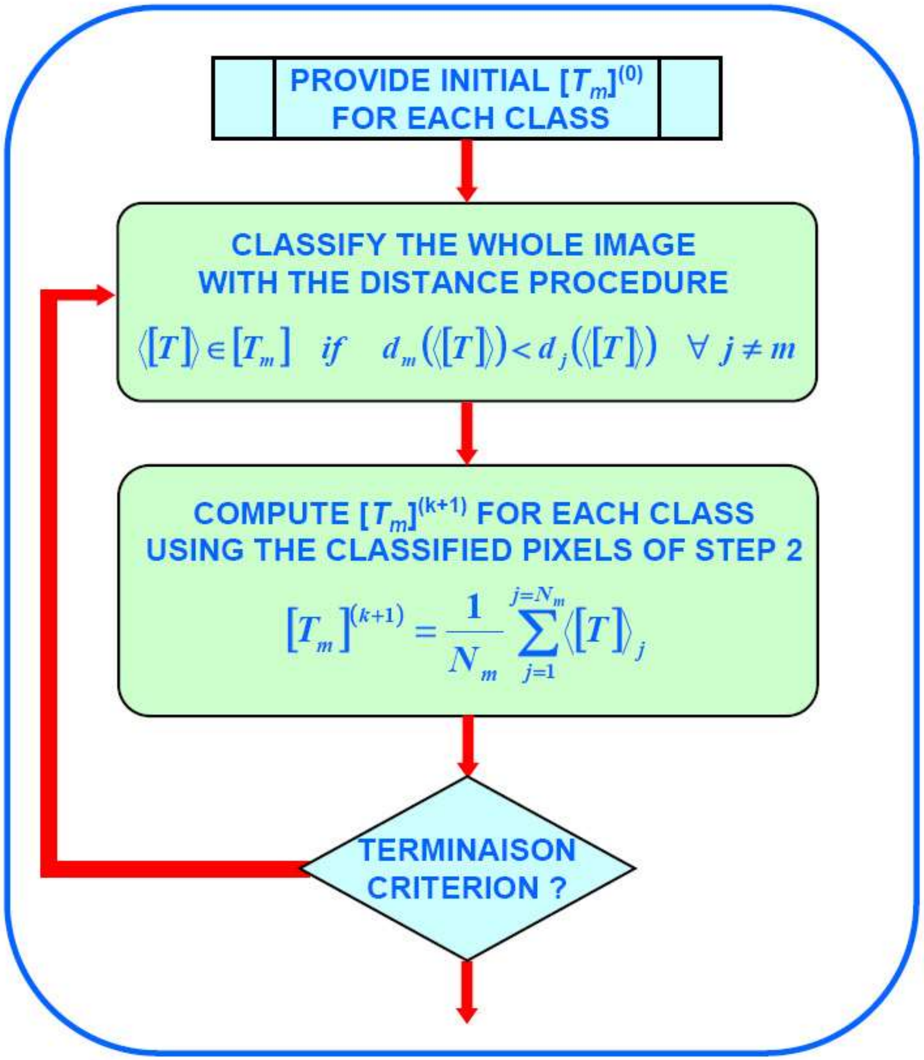
Unsupervised Classification based on the H / A / α Decomposition

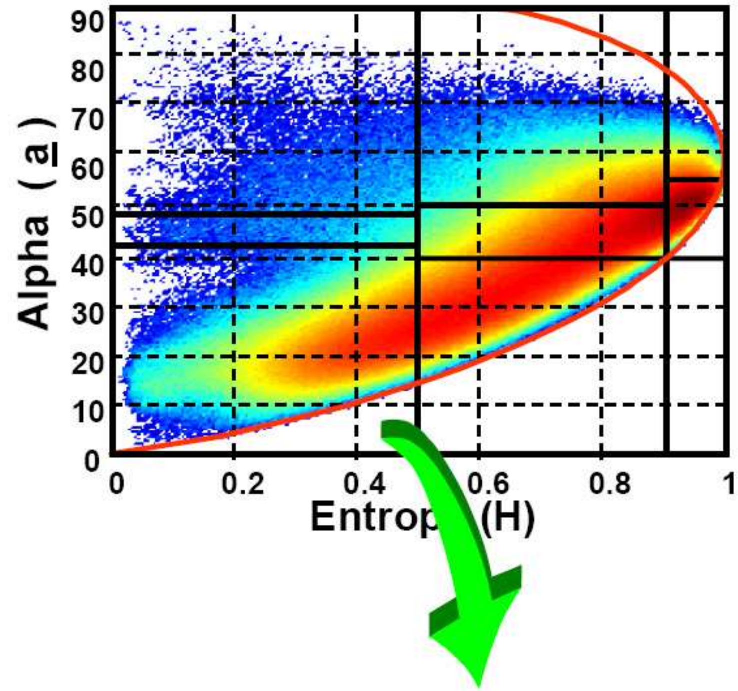
- **Disadvantage of H / A / α classification schemes:**
  - H / α classification space is sub-devided into 9 basic zones
  - Location of the boundaries is fairly arbitrary and generic
  - Therefore, H / A / α classification is not optimal and more advanced ways for determining class boundaries are sought.

- **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:**



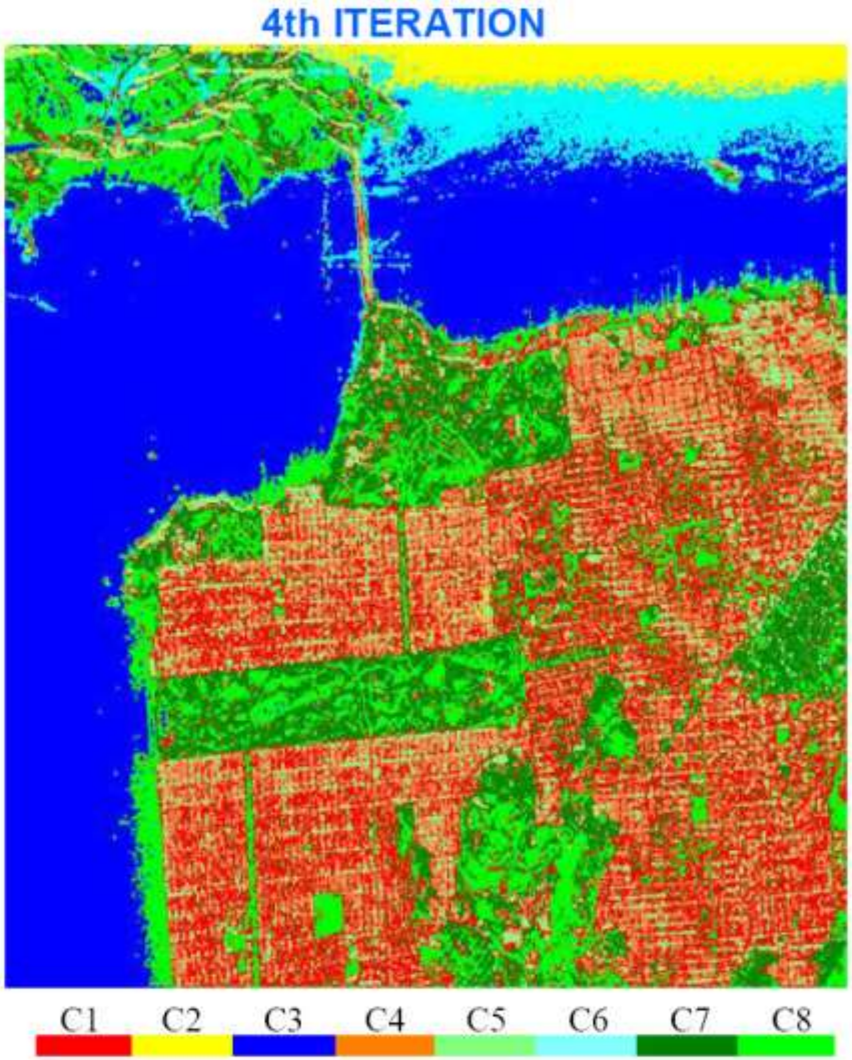


$$[T_m]^{(0)} = \frac{1}{N_m} \sum_{k=1}^{k=N_m} \langle[T]\rangle_k$$

Cluster Center of the class *m* (Lee 1998)

Unsupervised Classification based on the H / A / α Decomposition

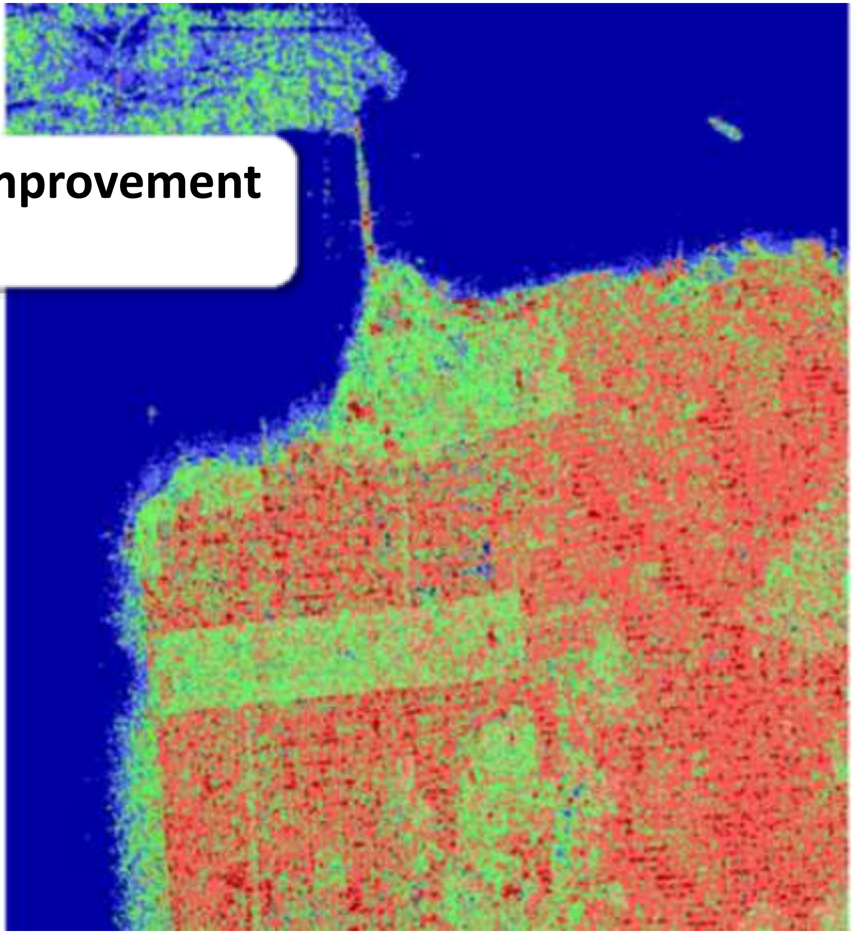
- **Example of k-mean classification procedure:**



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 Wavelength

- **Different penetration in different frequencies produce different polarimetric signatures**

C-band data: Polarimetric data is volume dominated

Australian Pasture

4th Iteration (15 classes)

Courtesy of J.S. Lee

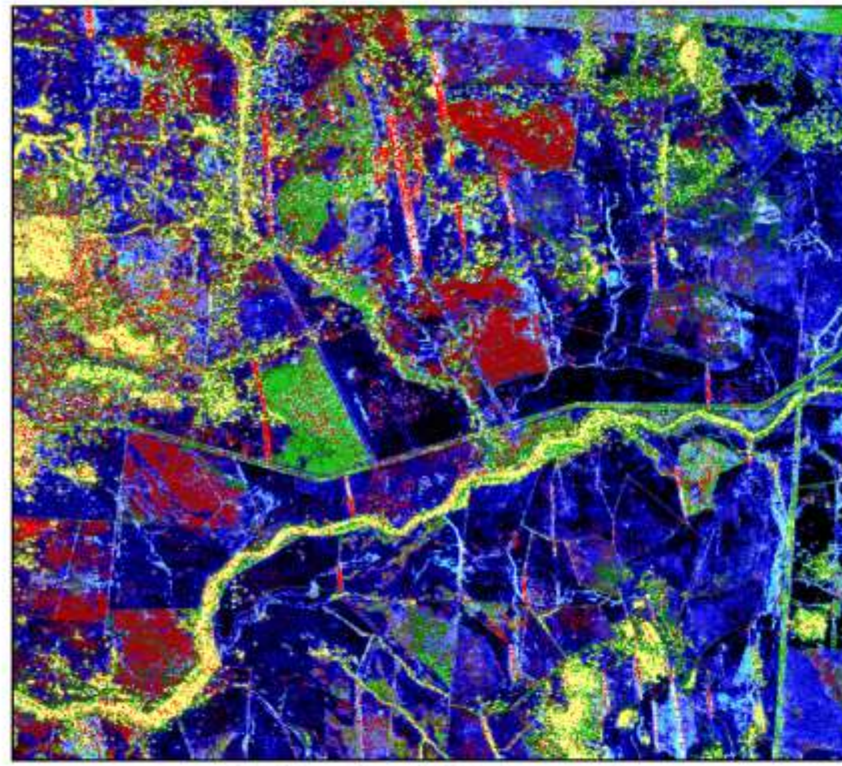
Polarimetric Classification

The Role of the Observation Wavelength

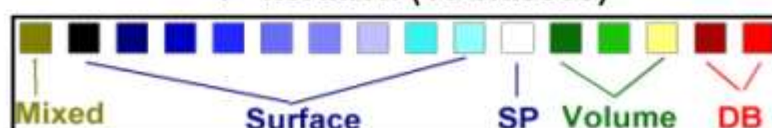
- **Different penetration in different frequencies produce different polarimetric signatures**

L-band data: Higher penetration causes more surface signal

Australian Pasture



4th Iteration (15 classes)



Courtesy of J.S. Lee

QUESTIONS?

UP NEXT: WHERE TO GET SAR DATA