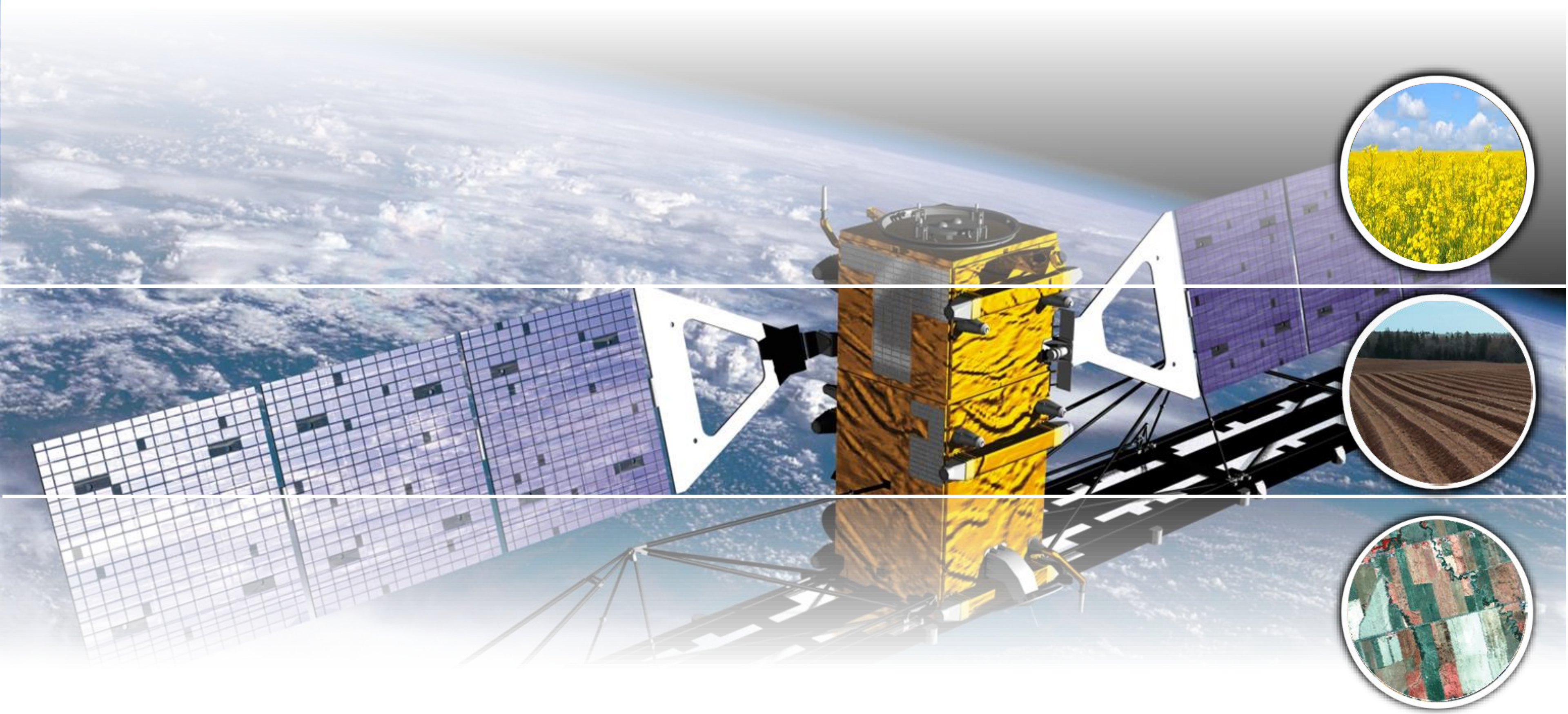


Lecture 3: SAR Polarimetry

Carleton University
Canada's Capital University

Natural Resources Canada
Ressources naturelles Canada

CSA ASC

Agriculture and Agri-Food Canada
Agriculture et Agroalimentaire Canada

SAR Polarimetry

SAR Polarimetry is the science of acquiring, processing and analyzing the polarization state of an electromagnetic field including the magnitude and ***relative phase****. SAR polarimetry is concerned with the utilization of polarimetry in radar applications.*

DLR-HR

Information source: Wolfgang-Martin Boerner

Fully Polarimetric SAR

- Fully polarimetric SAR systems: two orthogonal wave polarizations on **both** transmit and receive
- Typically these two orthogonal polarizations are H and V
- **Transmit**: alternating pulses of H and V (switching)
- **Receive**: H and V intensity is recorded simultaneously AND the relative phase between H and V is recorded

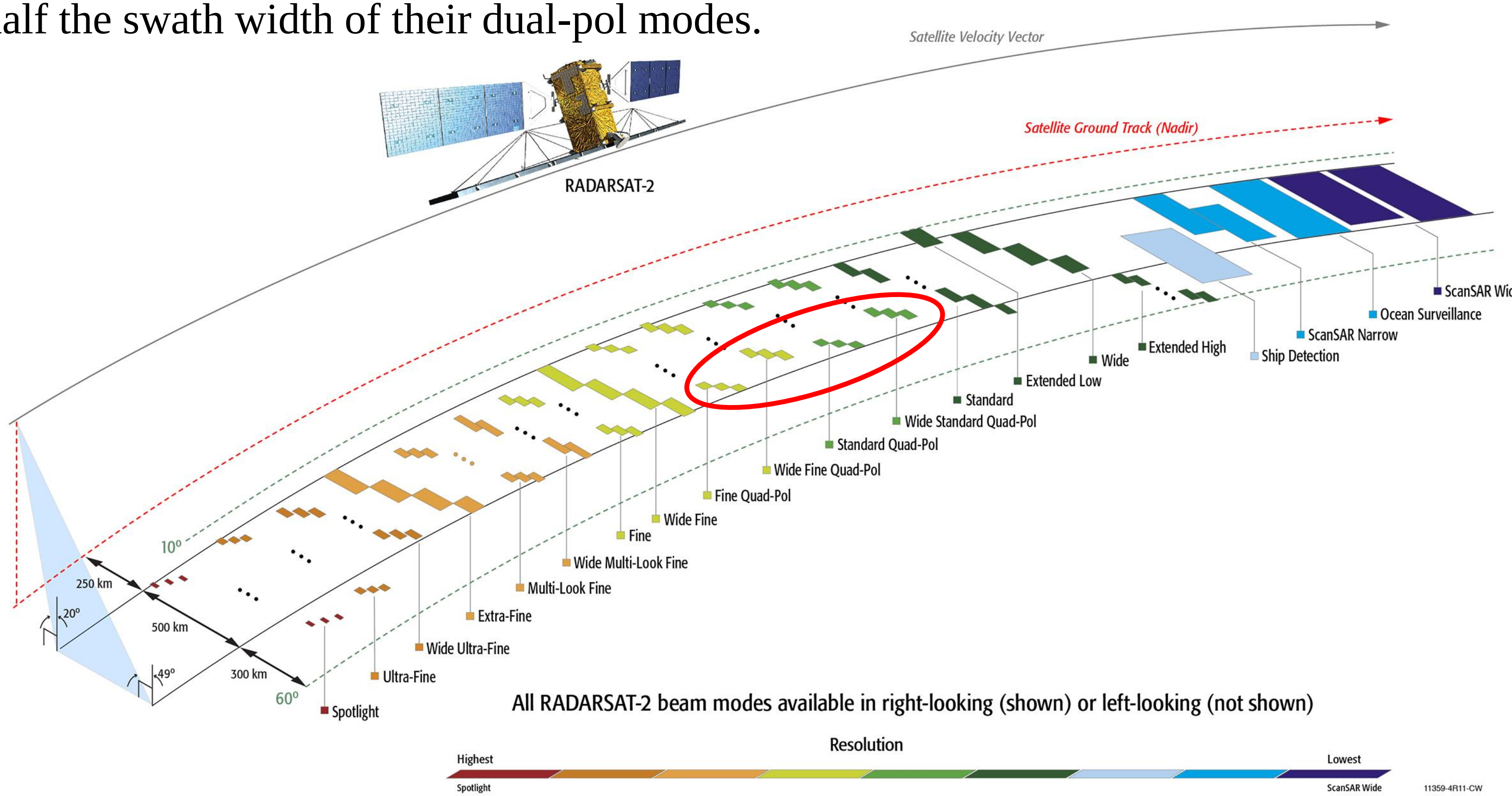
Receive Polarization

Transmit Polarization

	H or V	H and V	H and V **and relative phase**
H or V	Single [1] Pol	Dual [2] Pol	**Dual Polarimetric**
H and V	Dual [2] pol	Quad [4] Pol	**Fully Polarimetric**

Limitations of Fully Polarimetric SAR

- Requires twice the pulse repetition frequency (data rate) and power usage of a dual-pol SAR system since fully polarimetric SAR alternates the transmission of two orthogonal polarizations.
- For spaceborne platforms, the available power and data rate are extremely limited.
- To keep power usage constant, most spaceborne platforms use fully polarimetric modes with half the swath width of their dual-pol modes.



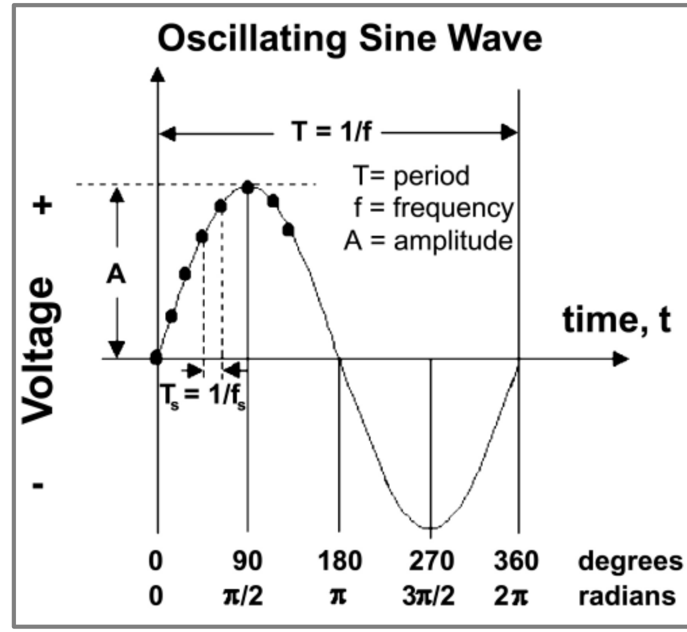
RADARSAT-2 Modes

Beam modes	Nominal swath width (km)	Maximal spatial resolution (m)
Selective Single or Dual Polarization **Transmit H and/or V, receive H and/or V**		
Fine	50	8
Wide Fine	150	8
Standard	100	25
Wide	150	25
ScanSAR Narrow	300	50
ScanSAR Wide	500	100
Ocean Surveillance	530	Variable
Polarimetric **Transmit H and V on alternate pulses /** **receive H and V on any pulse**		
Fine Quad-Pol	25	12
Wide Fine Quad-Pol	50	12
Standard Quad-Pol	25	25
Wide Standard Quad-Pol	50	25

Polarimetry – It's All About Phase

Recall from SAR Basics

- **Phase**: the position of a point in time on a waveform cycle
- **Amplitude**: the maximum amount of displacement from the rest position.
- **Phase shift:** any change that occurs in the phase of one quantity, or in the phase difference between two or more quantities.



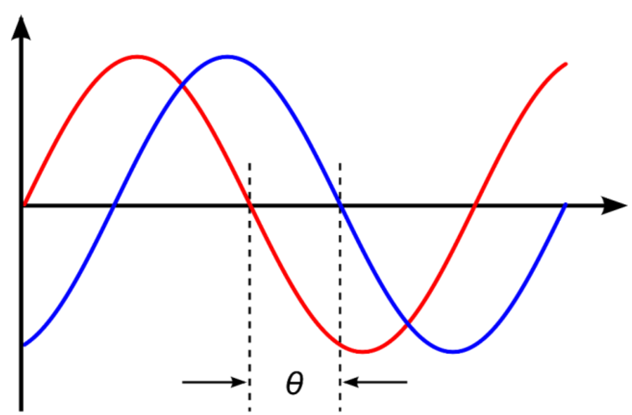
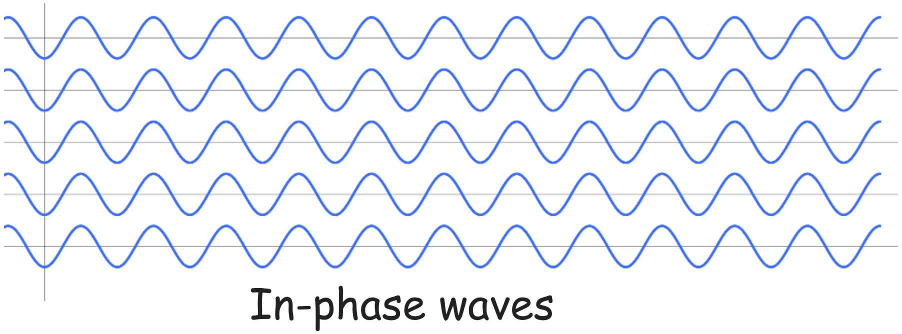


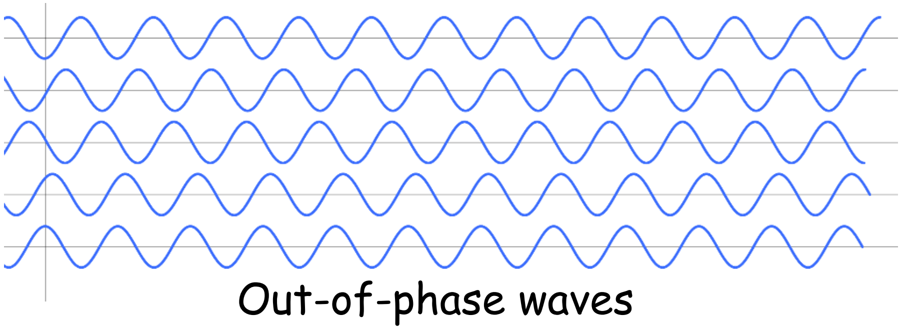
Image source: www.nist.gov/time-and-frequency-services/p

Image source: www.commons.wikimedia.org/w/index.php?curid=6007495

More About Phase

Phase difference: the difference between two waves having the same frequency and referenced to the same point in time. The amount by which waves are out of phase with each other can be expressed in degrees from 0° to 360°, or in radians from 0 to 2π.



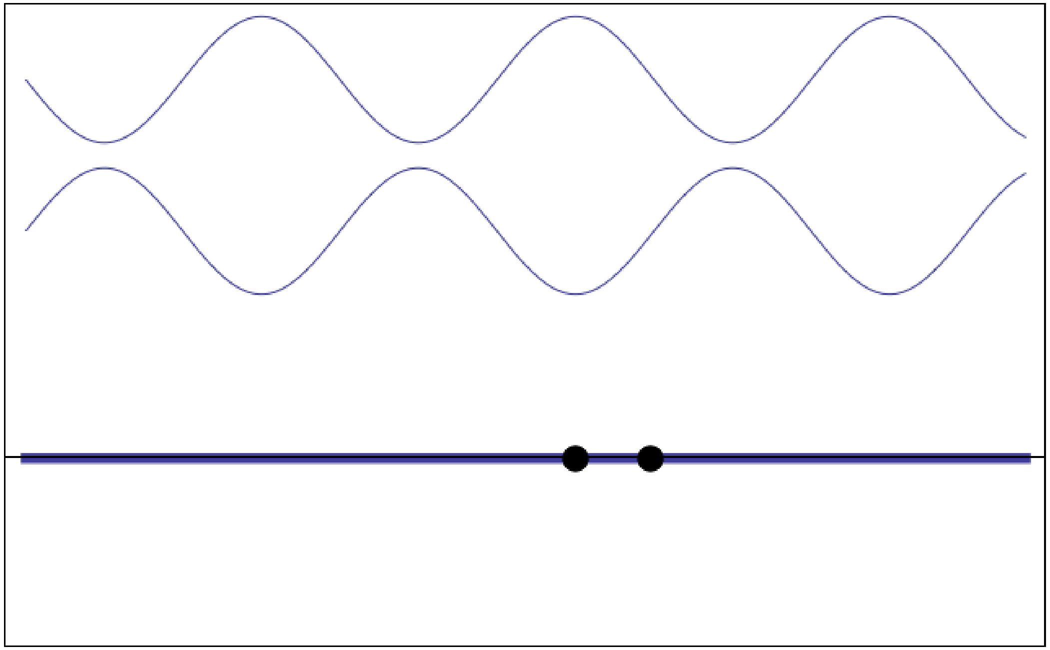


Coherency: two waves are perfectly coherent if they have a constant phase difference and the same frequency

Image source: www.commons.wikimedia.org/wiki/File:Sine_waves_same_phase.svg#/media/File:Sine_waves_same_phase.svg

Interference

- Two waves of same frequency superpose to form a resultant wave of greater, lower, or the same amplitude
- Waves perfectly in phase: signals augment each other.
- Waves slightly out of phase: overall signal is diminished (destructive interference)
- Waves out of phase by 180°: two waves exactly cancel each other.



Summation of two sine waves of the same frequency but different phases. As $\Delta\varphi \rightarrow 180°$ (out-of-phase) the two waves destructively interfere, yielding a net signal that is nearly zero.

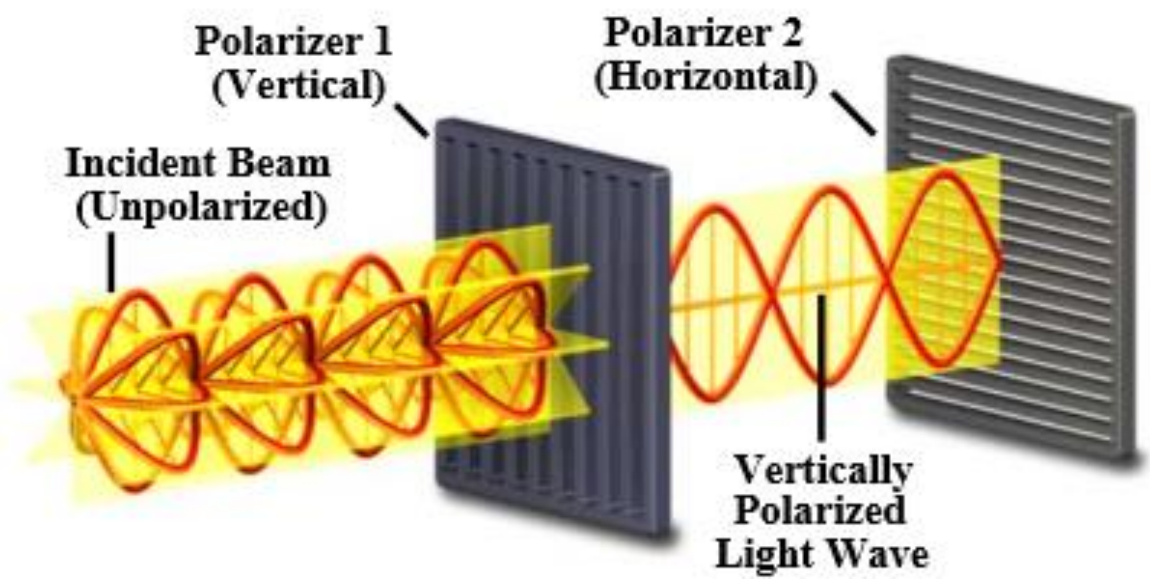
Image source: https://www.acs.psu.edu/drussell/demos/superposition/superposition.html

The Energy Source: Completely, Partially or Un-Polarized?

- Individual atoms in a source act independently and can emit EM waves which are out of phase and in different polarizations
- The superposition or summation of these emissions creates a wave whose phase and polarization vary randomly and rapidly in space and time

Unpolarized: direction of polarization changes rapidly and randomly

Partially polarized: when a wave consists of the superposition of many different polarizations but one or more polarizations dominate



- SARs: the oscillator generates a **completely polarized** wave (the polarization is known and constant)

Image source: www.microscopyu.com/techniques/polarized-light/introduction-to-polarized-light

Then What Happens: The Scattered Wave

- The wave incident upon the target arrives completely polarized
- **The physics remains the same**: if the target is composed of randomly oriented elements (leaves, needles, trunks, stalks etc) the waves scattered by these individual elements will vary in phase and polarization
- The superposition or summation of these scatterers within a resolution cell creates a wave whose phase and polarization vary randomly in space and time
- The scattered wave can be unpolarised or partially polarized

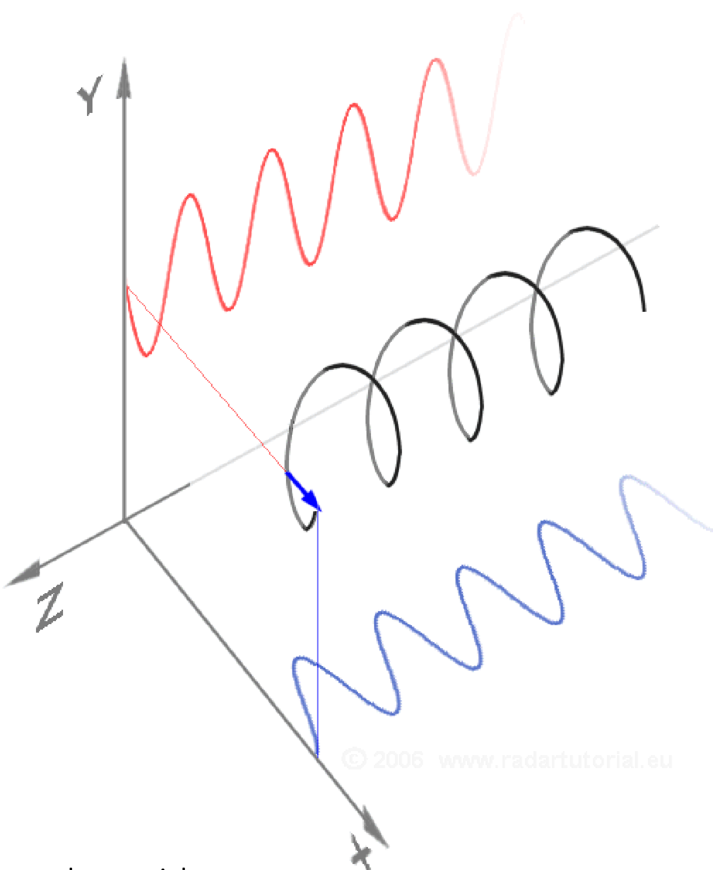
The Good News

Fully polarimetric SARs can measure this degree of polarization.

Would differences in the architecture of tree canopies cause differences in the amount of unpolarised and partially polarized scattering?

Elliptically Polarized Waves

- Typically waves are elliptically polarized. Linear and circular polarizations are special cases.
- For circular polarizations, there is a 90° phase shift between the H and V feeds.
- This phase shift causes the tip of the electric field vector to rotate as the wave propagates

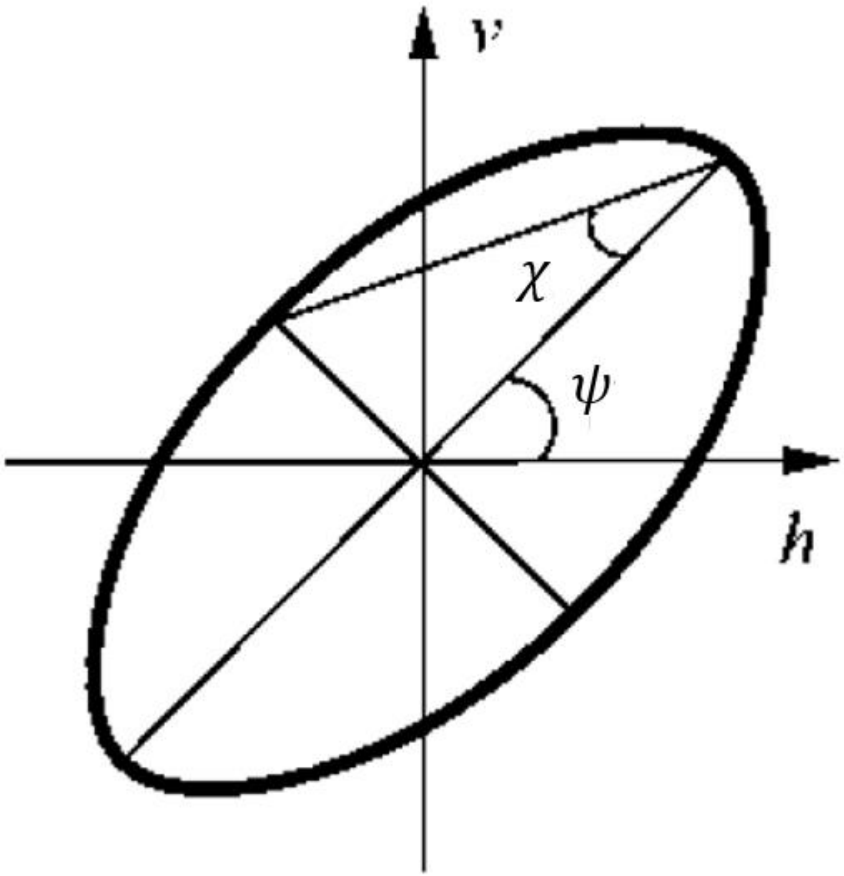


A circularly polarized wave as a sum of two linearly polarized components 90° out of phase.

Image source: radartutorial.eu

Polarization Ellipse

Any wave can be characterized by two parameters.



Orientation angle

$$= [-90^{\circ} \leq \psi \leq 90^{\circ}]$$

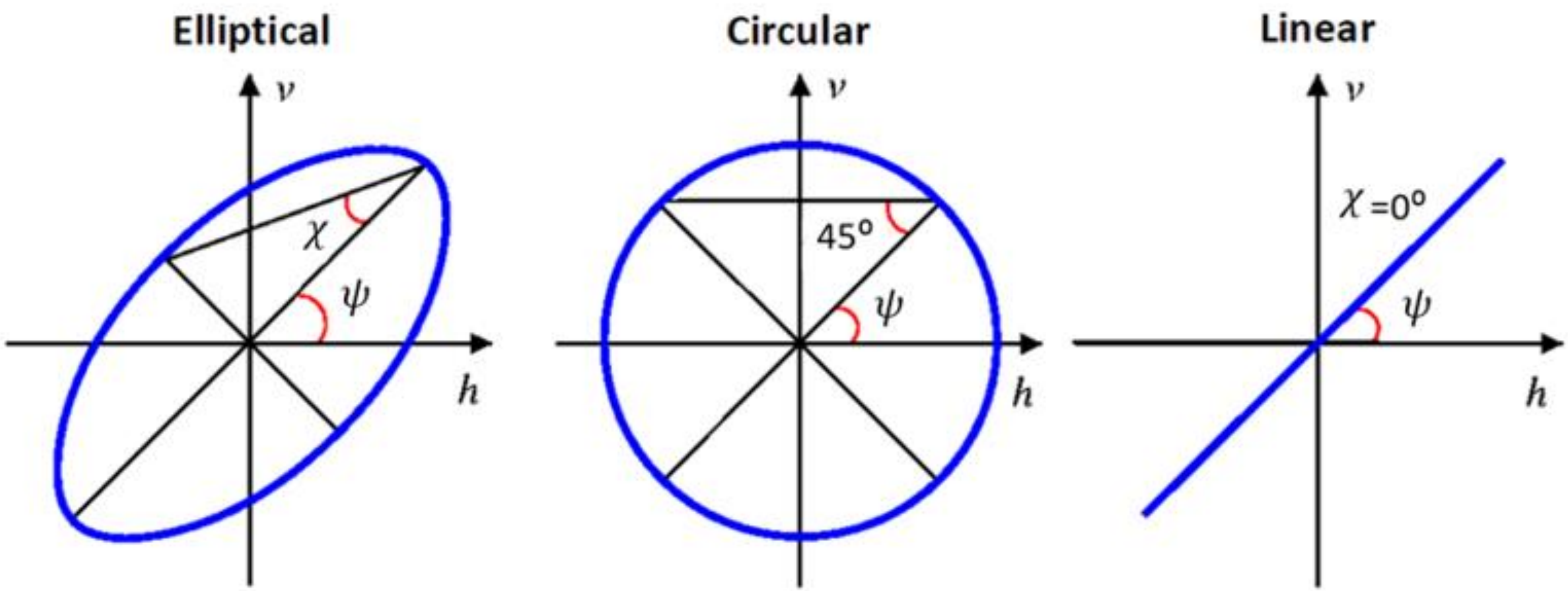
Ellipticity angle

$$= [-45^{\circ} \leq \chi \leq 45^{\circ}]$$

Orientation angle (ψ)

Ellipticity angle (χ)

Canonical States of Polarization Ellipse



	Horizontal	Vertical	Linear at θ°	Left Circular	Right Circular
Orientation angle :	0°	90°	θ°	-90° - 90°	-90° - 90°
Ellipticity angle :	0°	0°	0°	45°	-45°

Image source: https://eo-college.org/

Polarization Handedness

- While propagating, elliptically and circularly polarized waves have a direction of rotation
- The “handedness” of the polarizations tells us whether the vector tip of the EM wave is rotating clockwise or counter clockwise

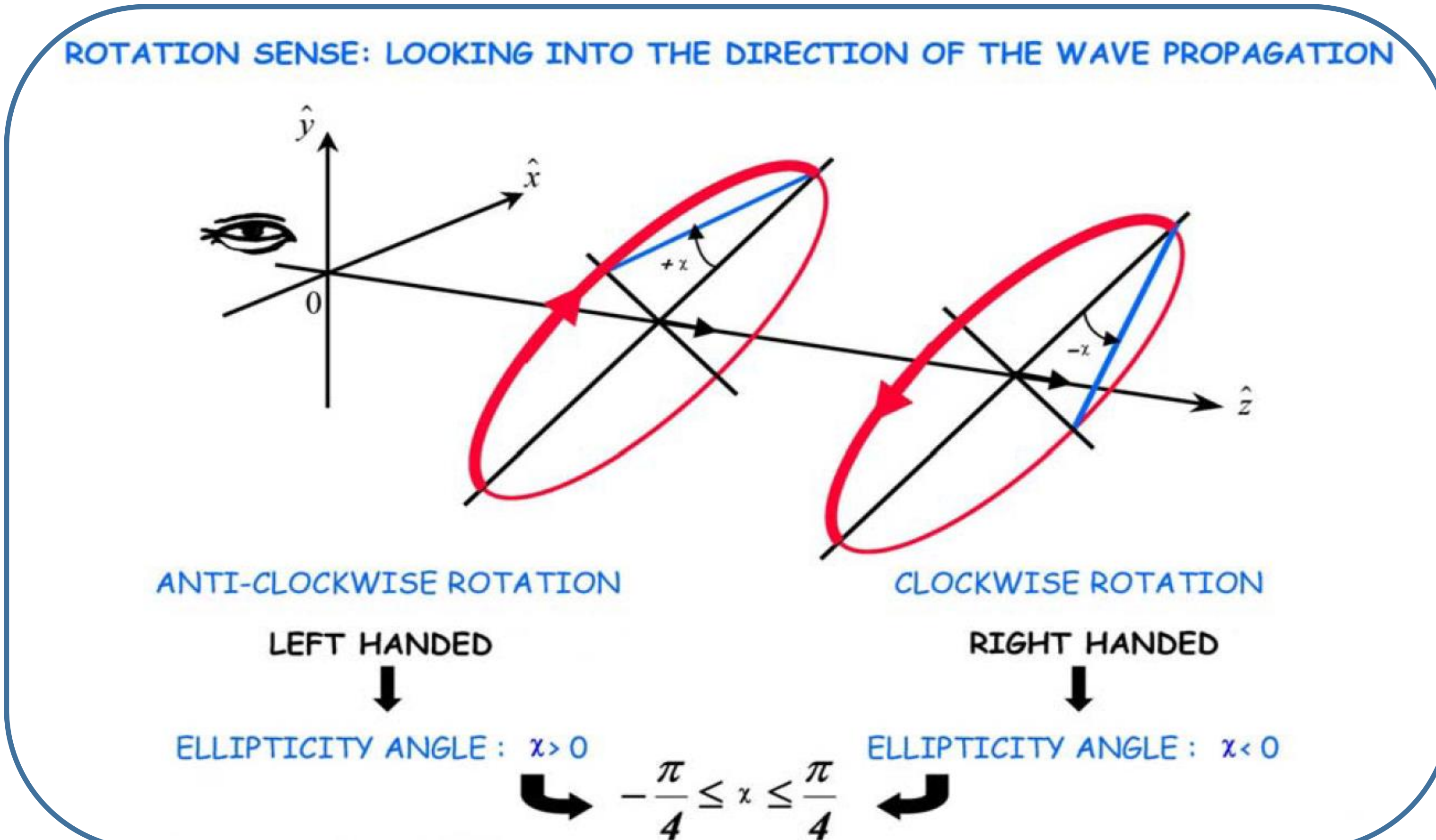
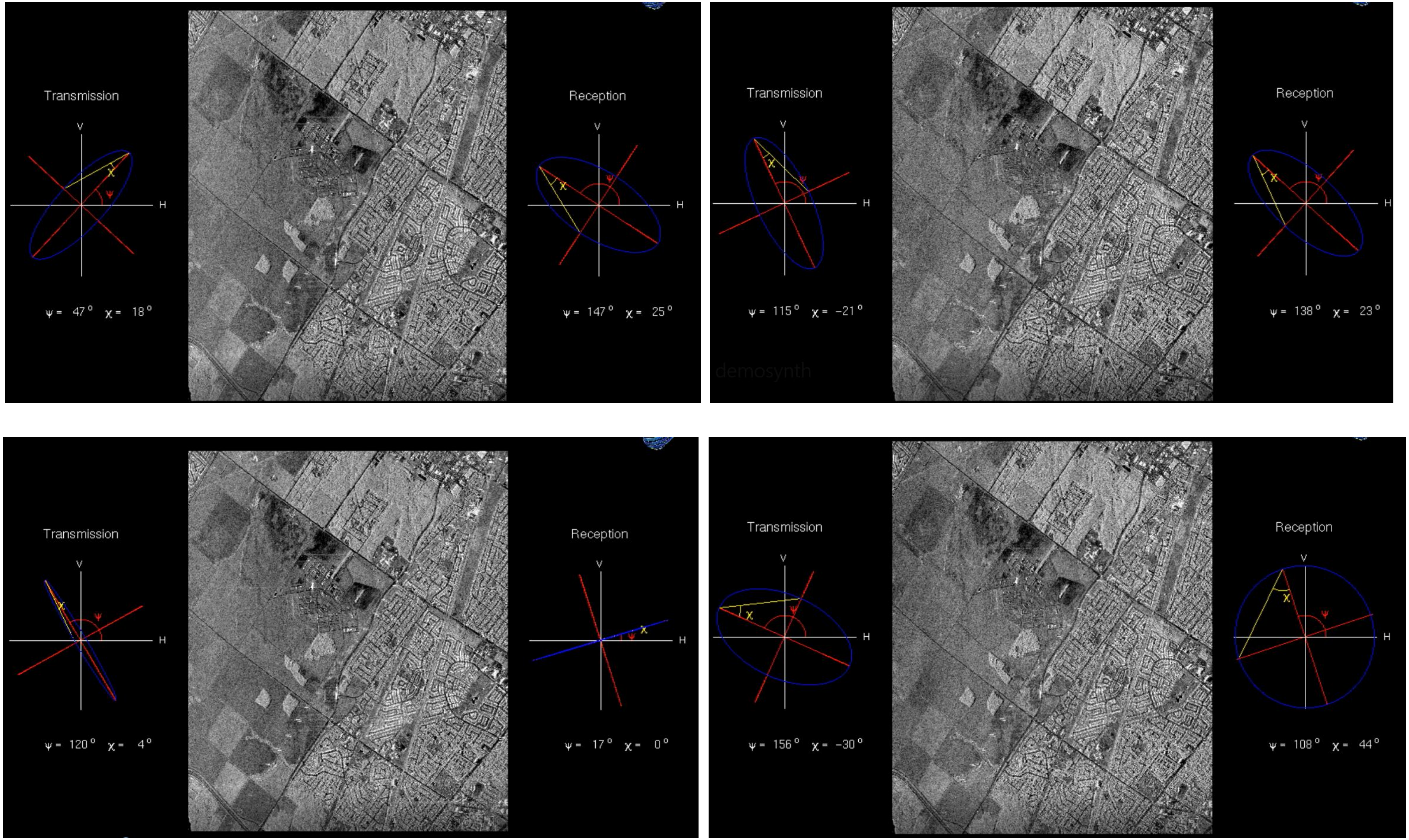


Image source: ESA Polarimetry Tutorial

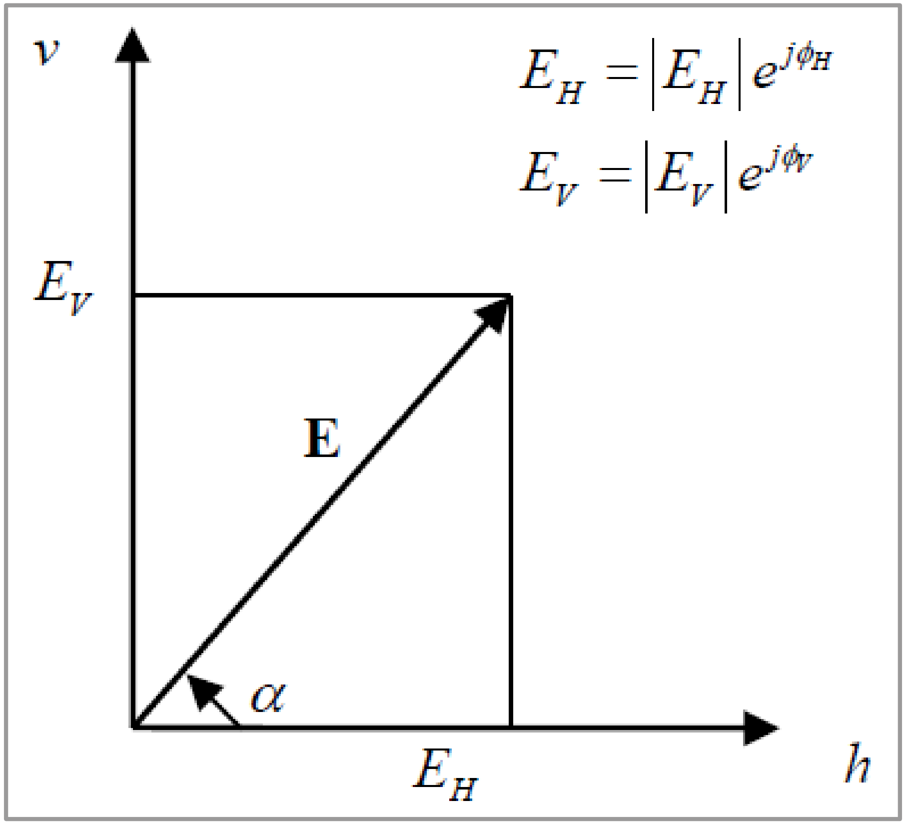


- Fully polarimetric SARs capture the complete scattering characteristics of the target

- Any transmit and receive polarization can be simulated
  - not only H or V, but any orientation
  - not only linear polarizations, but any elliptically polarized or circular polarized wave

Jones vector

- The Jones Vector is used to describe a **fully** polarized wave.
- It represents the amplitude and phase information of the two components of the electric field vector as a two-dimensional complex vector.



$|E|$ = amplitude
ϕ = phase

A **complex number** is a number that can be expressed in the form $a + bi$, where a and b are real numbers, and i is a solution of the equation $x^2 = -1$.

Stokes Parameters

- A set of values (S_0, S_1, S_2, S_3) that describe the **fully or partially** polarization state of an EM wave
- These parameters are derived from the Jones Vector.
- The Stokes parameters describe the total intensity (H and V directions) of the wave and its geometry.

$$S_0 = |E_H|^2 + |E_V|^2$$

$$S_1 = |E_H|^2 - |E_V|^2$$

$$S_2 = 2|E_H||E_V|\cos\phi_{HV}$$

$$S_3 = 2|E_H||E_V|\sin\phi_{HV}$$

$|E|$ = amplitude
ϕ = phase
ϕ_{HV}=the phase difference between H and V

$$\phi_{HV} = \phi_V - \phi_H$$

Stokes Parameters

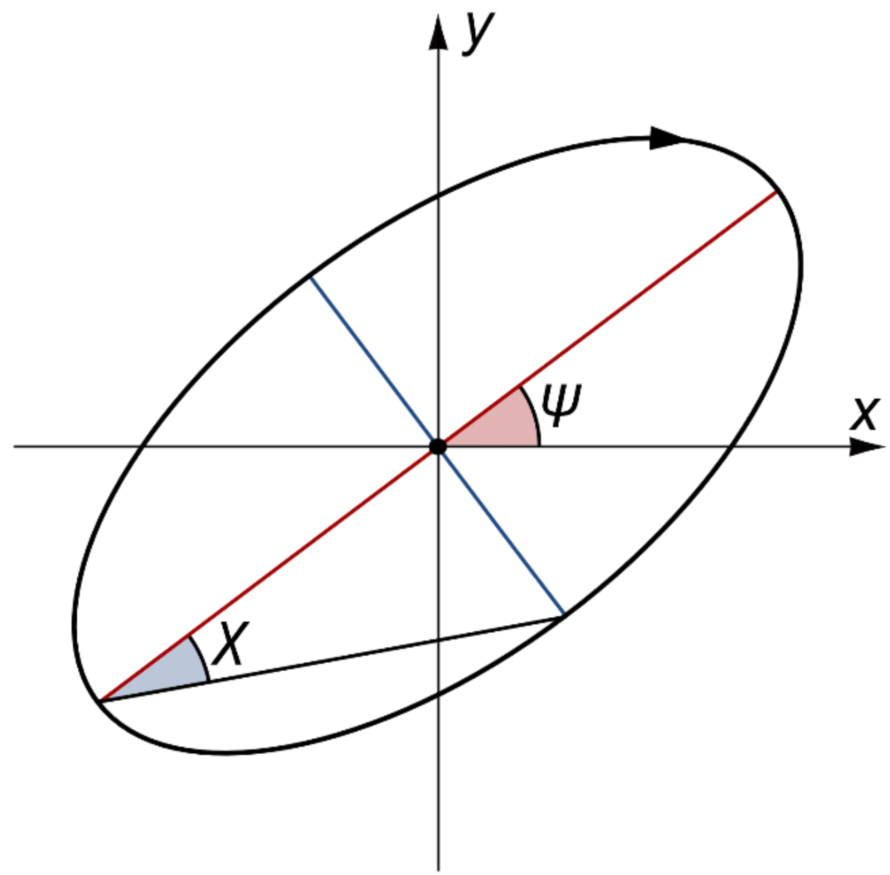
- A mathematically convenient alternative to describe a wave's total intensity (I), degree of polarization (p), orientation angle (ψ) and ellipticity angle (χ).

$$I = S_0$$

$$p = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0}$$

$$2\psi = \mathrm{atan}\frac{S_2}{S_1}$$

$$2\chi = \mathrm{atan}\frac{S_3}{\sqrt{S_1^2 + S_2^2}}$$



p = degree of polarization
I = intensity
ψ = orientation angle
χ = ellipticity angle

Stokes Vector

- The Stokes parameters are often combined into a vector, known as the Stokes vector.
- I, Q, U and V are sometimes used to represent the stokes parameters.

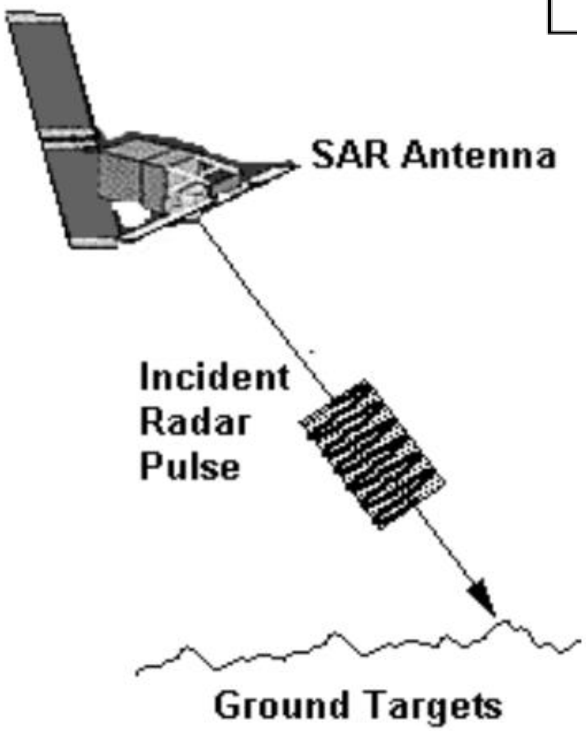
$$\vec{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

Jones Vector of Scattered Wave

Incident Wave

Jones vector of incident wave (E^I)

$$\begin{bmatrix} E_H^I \\ E_V^I \end{bmatrix}$$



Scattered Wave

Jones vector of scattered wave (E^S)

$$\begin{bmatrix} E_H^S \\ E_V^S \end{bmatrix}$$

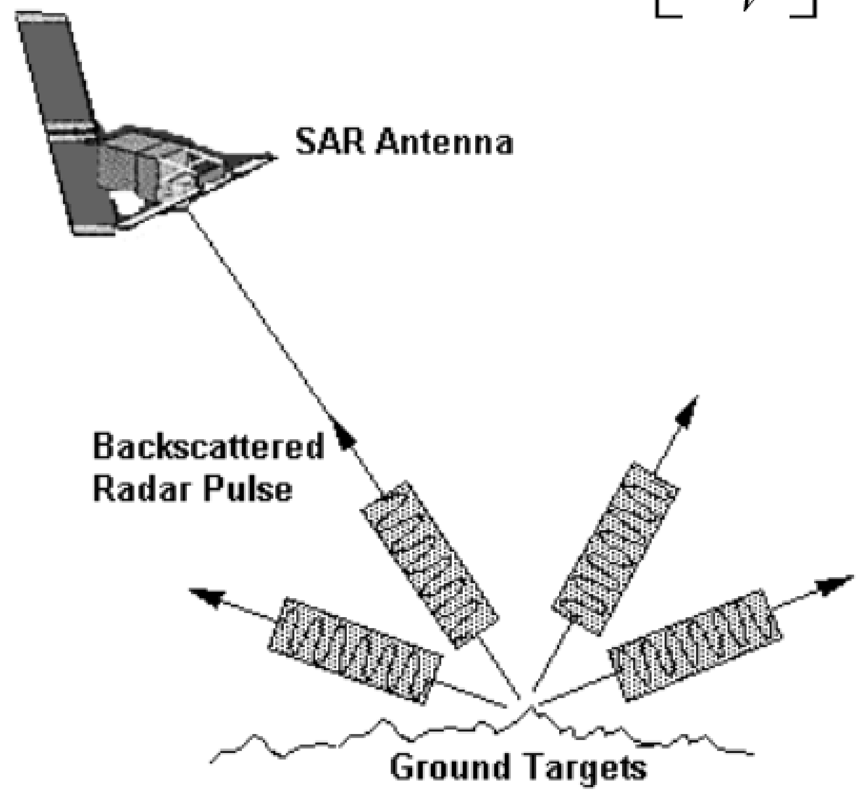


Image source: https://crisp.nus.edu.sg/~research/tutorial/mw.htm

Scattering Matrix

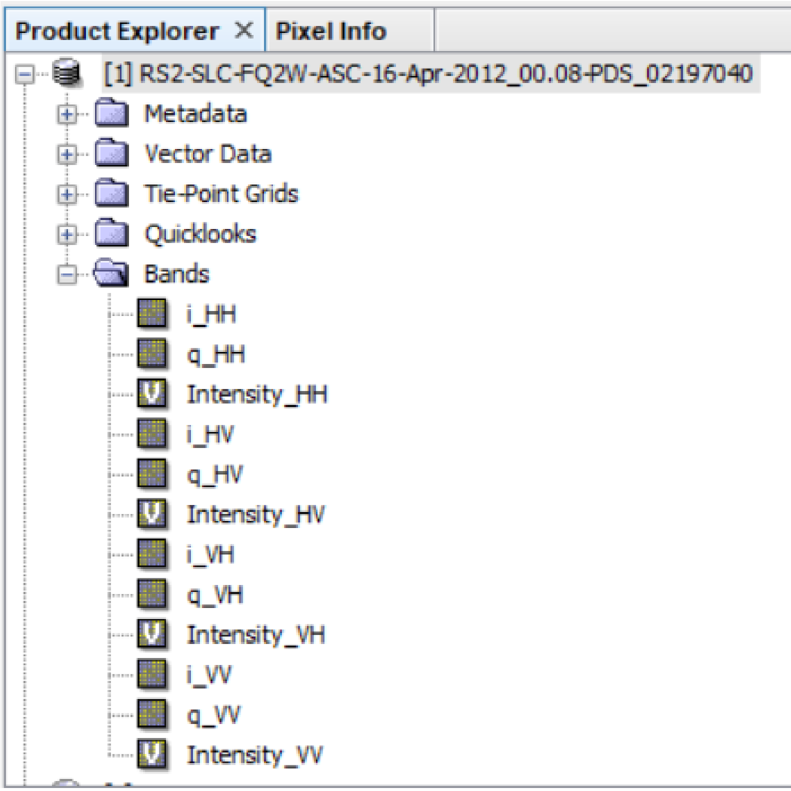
The scattering matrix is used to derive the scattered wave from the incident wave

<u>2×2 Complex Scattering Matrix</u>

$$\begin{bmatrix} E_H^S \\ E_V^S \end{bmatrix} = \frac{e^{ikr}}{r} \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} \begin{bmatrix} E_H^I \\ E_V^I \end{bmatrix}$$

r = distance from target to receiver
k= wave number
λ = wavelength
S = scattered
I = incident

$$k = \frac{2\pi}{\lambda}$$



Scattering Matrix

$$[S] = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{HV} & S_{VV} \end{bmatrix}$$

- The scattering matrix contains all the information about the scattering process and the scatterer itself.
- The scattering matrix is used to derive two different types of information. Those derive directly from the Scattering matrix (First Order) and those derived indirectly from the Covariance and Coherency matrices (Second Order).

Observations

First Order Parameters: Backscattering Cross Section σ^0; Polarimetric phase differences.

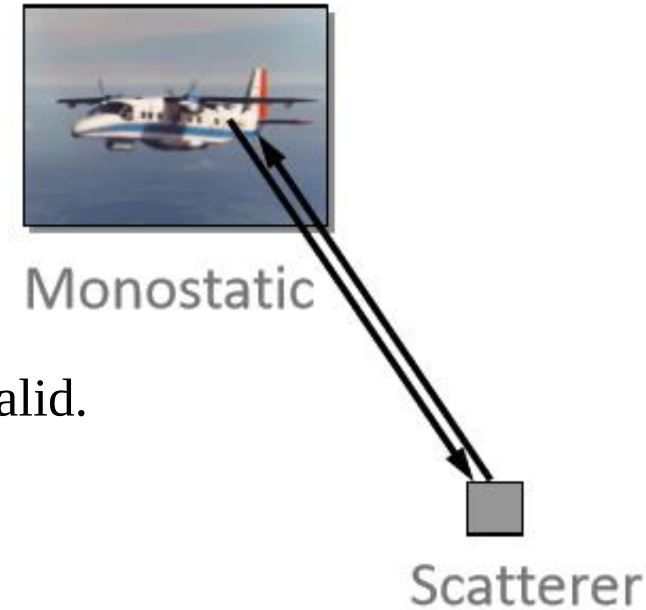
Second Order Parameters: Polarimetric decomposition parameters.

$$\sigma^0 \, (dB) = 10. \, Log_{10} \, (energy \ ratio)$$

whereby

$$\text{energy ratio} = \frac{\text{received energy by the sensor}}{\text{“energy reflected in an isotropic way”}}$$

Reciprocity



- Monostatic antenna is when the transmit and receive antenna are the same.
- For Monostatic antenna the Reciprocity condition is valid.

Reciprocity Theorem

$$S_{HV} = S_{VH} = S_{XX}$$

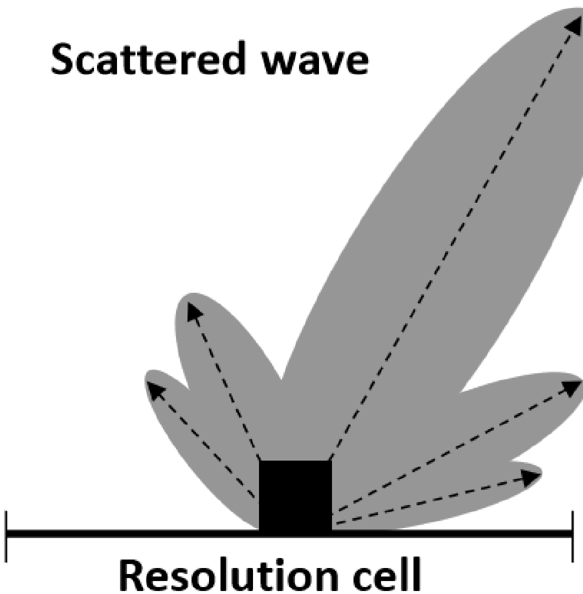
$$\begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} \Rightarrow \begin{bmatrix} S_{HH} & S_{XX} \\ S_{XX} & S_{VV} \end{bmatrix}$$

$$TP = Span\ ([S]) = |S_{HH}|^2 + |S_{HV}|^2 + |S_{VH}|^2 + |S_{VV}|^2 = \underbrace{|S_{HH}|^2 + 2|S_{HV}|^2 + |S_{VV}|^2}_{\text{Reciprocity condition}}$$

TP = Total Power

Coherent and Incoherent Scatterer

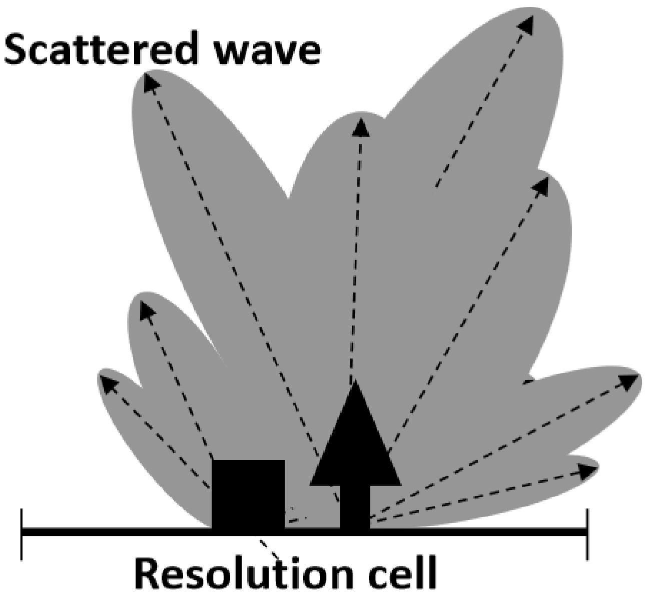
Described by the scattering matrix



Single Scatterer, or
Deterministic Scatterer
or Coherent Scatterer

$$\begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix}$$

Cannot be described by the scattering matrix

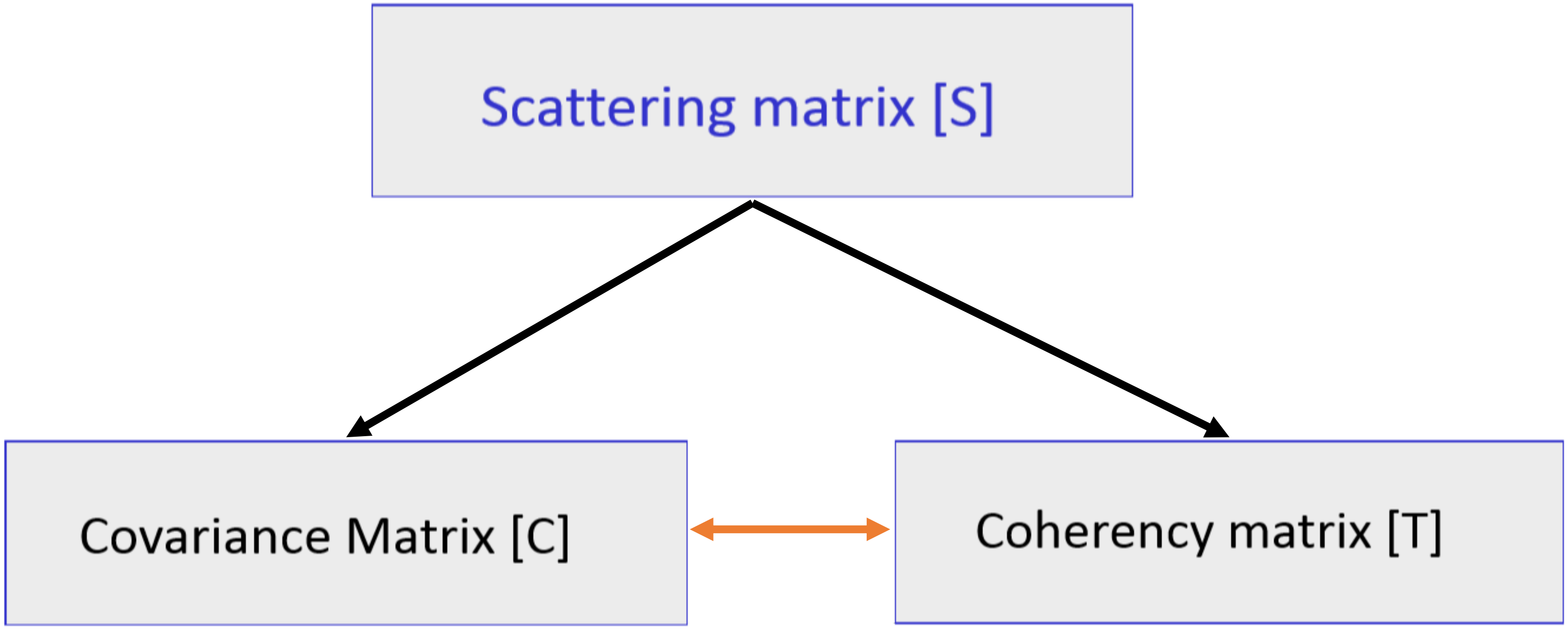


Multiple Targets, or
Undeterministic Scatterer
or Incoherent Scatterer

$$\begin{bmatrix} ? & ? \\ ? & ? \end{bmatrix}$$

Image source: https://eo-college.org/

Polarimetric Scattering Descriptors



- The Covariance and Coherency matrices are used to generate the second-order parameters including the decompositions.
- Users can convert between the Covariance and Coherency matrices.

It is not possible to return to the Scattering Matrix [S].

Covariance Matrix

- Because the Scattering matrix cannot describe an incoherent scatterer, the Covariance matrix is used.
- To generate the covariance matrix, the Lexicographic scattering matrix has to be converted to a simplified target vector under the reciprocity condition.

Lexicographic (L) Scattering Vector

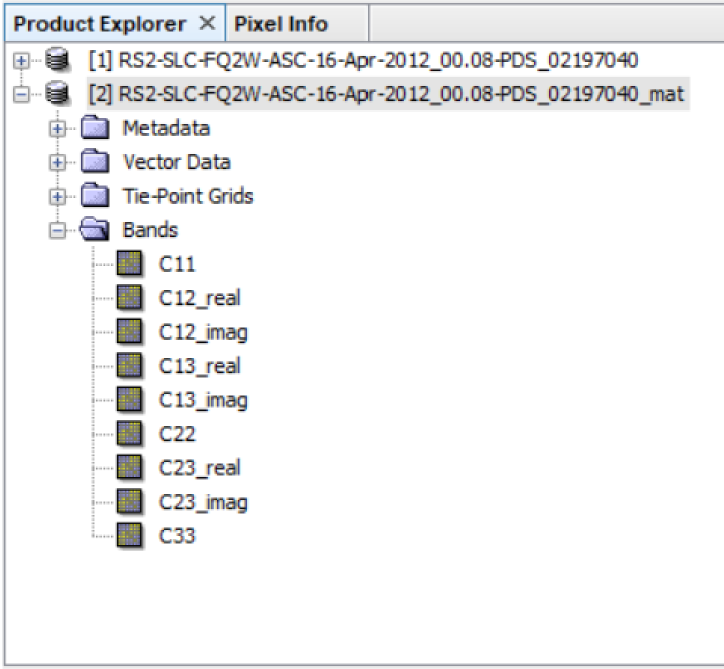
$$\vec{k}_{4L} = \begin{bmatrix} S_{HH} \\ S_{XX} \\ S_{XX} \\ S_{VV} \end{bmatrix} \Rightarrow \vec{k}_{3L} = \begin{bmatrix} S_{HH} \\ \sqrt{2}S_{XX} \\ S_{VV} \end{bmatrix}$$

$$XX = HV = VH$$

Note: The factor $\sqrt{2}$ is required to keep the vector Span invariant.

Covariance Matrix

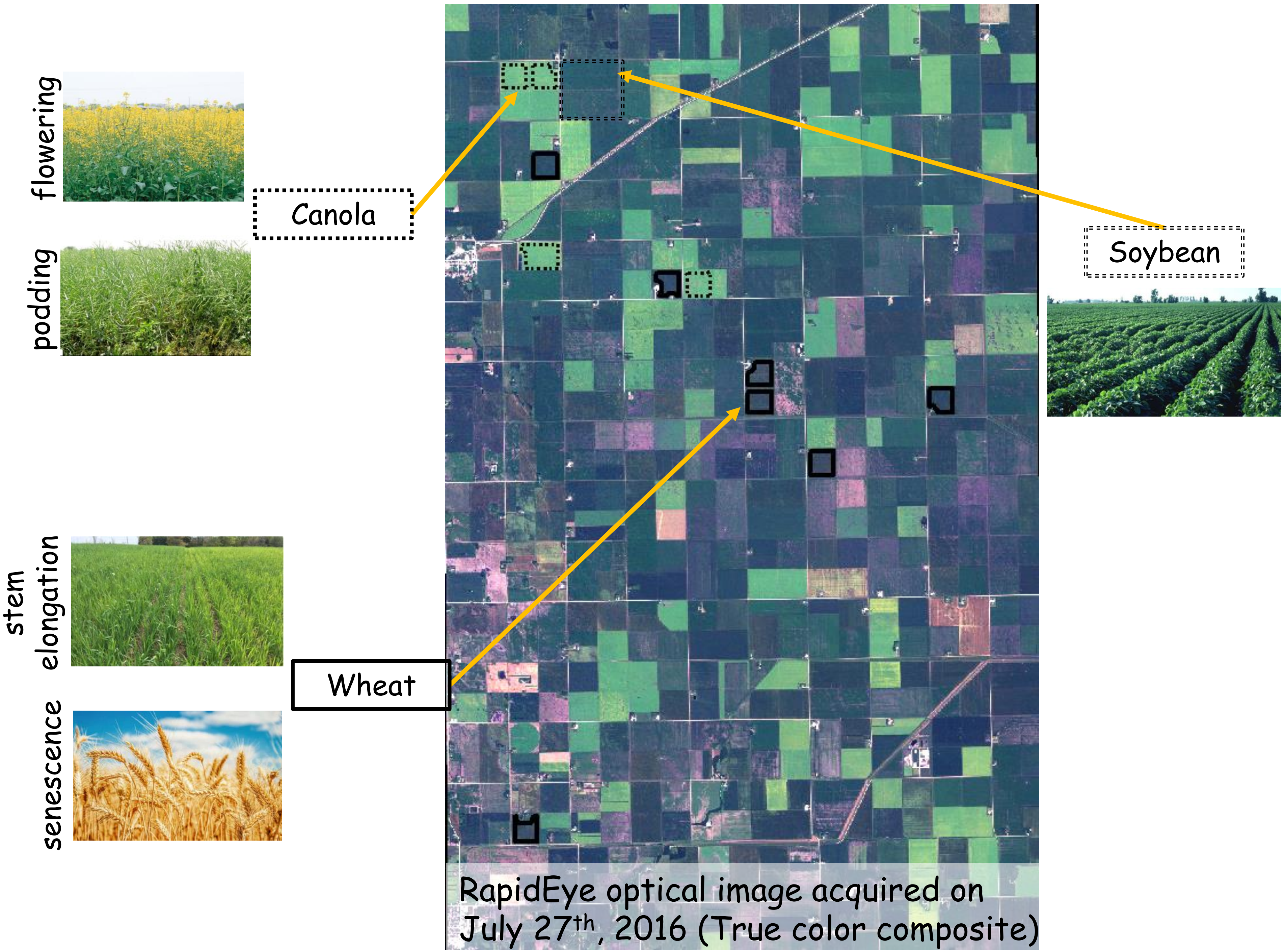
- The Covariance matrix is obtained by multiplying the Scattering vector by its conjugate transpose.
- The Covariance matrix is a 3 by 3 matrix and contains 9 elements which the diagonal elements (real numbers) describe the intensities and the non-diagonal (complex numbers) describe the intensity and phase between different polarizations.



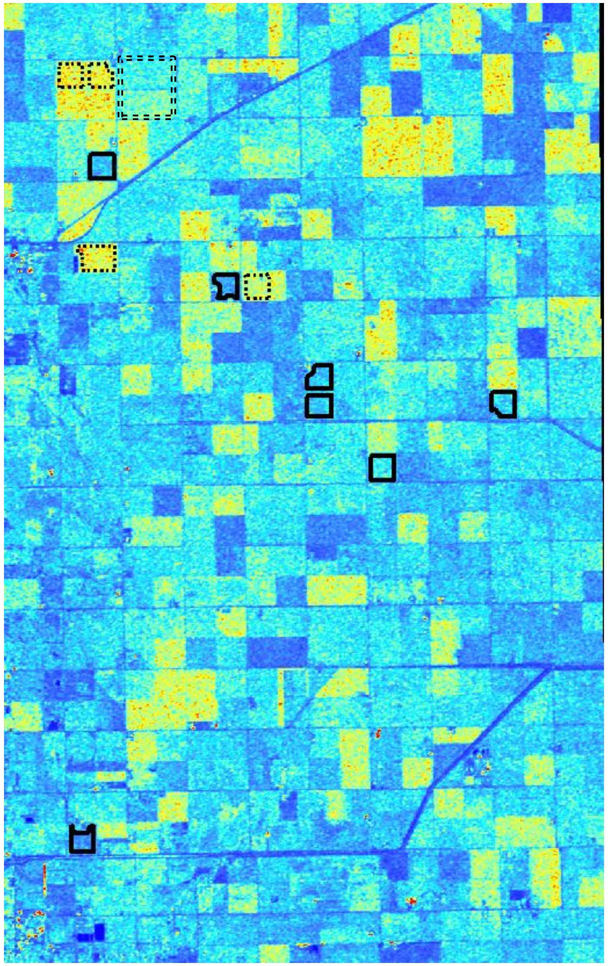
Lexicographic (L) Scattering Vector

$$[C] = \begin{bmatrix} S_{HH} \\ \sqrt{2}S_{XX} \\ S_{VV} \end{bmatrix} \begin{bmatrix} S_{HH}^* & \sqrt{2}S_{XX}^* & S_{VV}^* \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{12}^* & C_{22} & C_{23} \\ C_{13}^* & C_{23}^* & C_{33} \end{bmatrix}$$

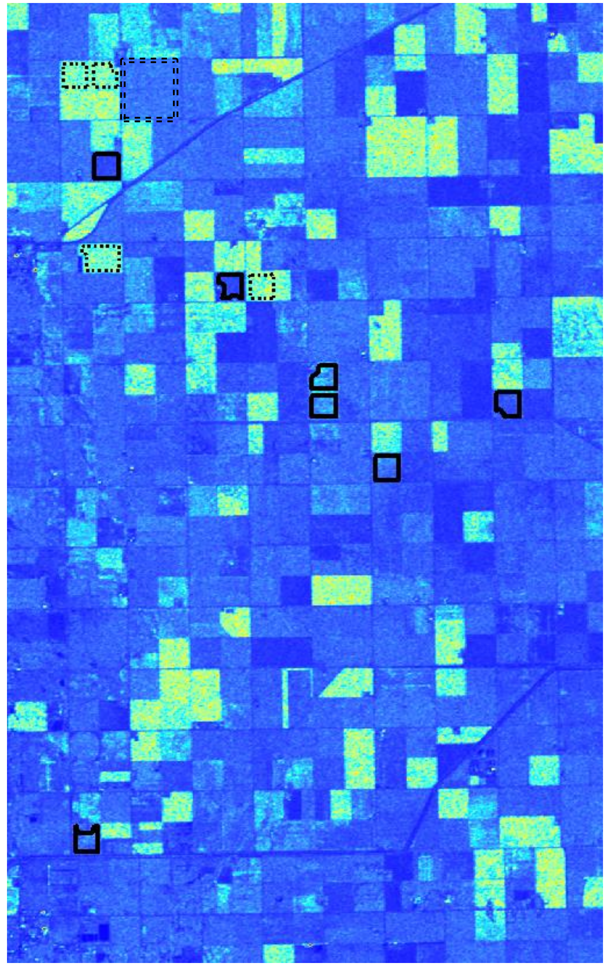
$$[C] = \begin{bmatrix} |S_{HH}|^2 & \sqrt{2}S_{HH}S_{XX}^* & S_{HH}S_{VV}^* \\ \sqrt{2}S_{HH}^*S_{XX} & 2|S_{XX}|^2 & \sqrt{2}S_{XX}S_{VV}^* \\ S_{HH}^*S_{VV} & \sqrt{2}S_{XX}^*S_{VV} & |S_{VV}|^2 \end{bmatrix}$$


flowering
podding
Canola
Soybean
stem elongation
senescence
Wheat
RapidEye optical image acquired on July 27th, 2016 (True color composite)

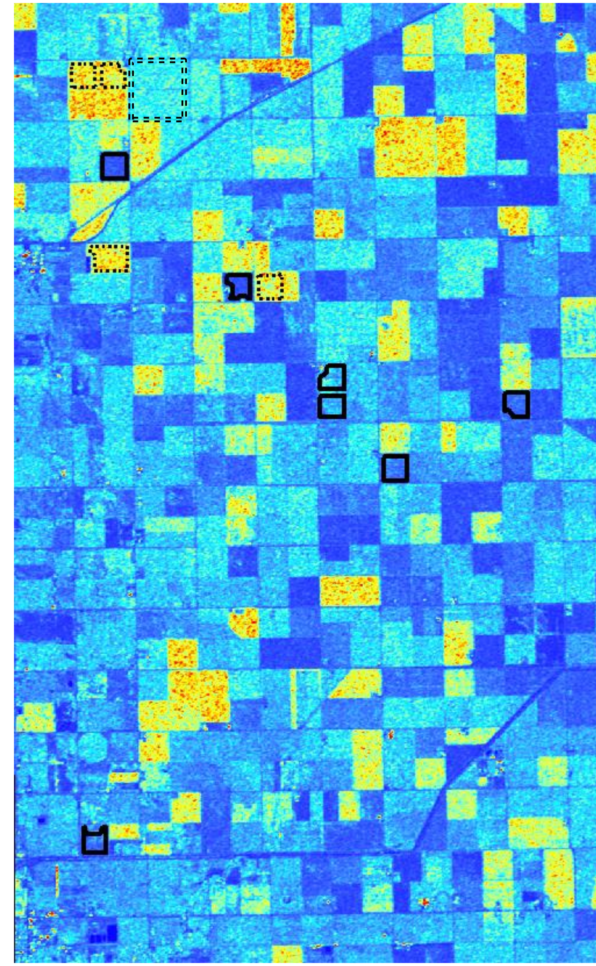
Covariance Matrix Elements



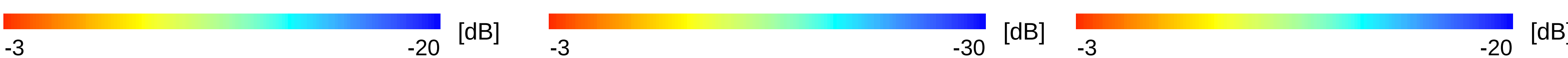
$$C_{11} = |S_{HH}|^2$$



$$C_{22} = 2|S_{XX}|^2$$



$$C_{33} = |S_{VV}|^2$$



Extracted from July 27th, 2016 RADARSAT-2 image

Coherency Matrix

- The Coherency matrix is obtained by multiplying the Pauli Scattering vector by its conjugate transpose.

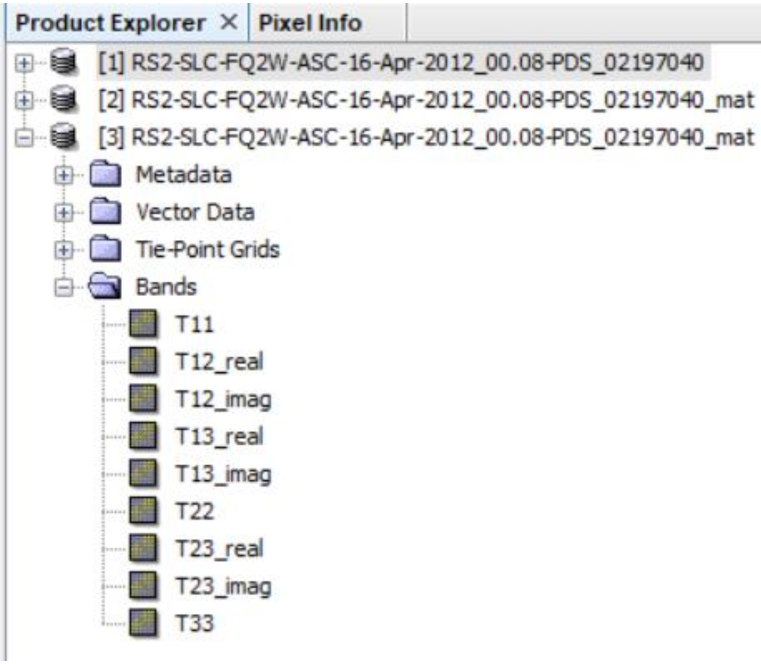
<u>Pauli (P) Scattering Vector</u>

$$\vec{k}_{4P} = \frac{1}{\sqrt{2}} \begin{bmatrix} S_{HH} + S_{VV} \\ S_{HH} - S_{VV} \\ 2S_{XX} \\ 0 \end{bmatrix}$$

$$\vec{k}_{3P} = \frac{1}{\sqrt{2}} \begin{bmatrix} S_{HH} + S_{VV} \\ S_{HH} - S_{VV} \\ 2S_{XX} \end{bmatrix}$$

Coherency Matrix

- The Coherency matrix is a 3 by 3 matrix and contains 9 elements which the diagonal elements (real numbers) describe the intensities and the non-diagonal (complex numbers) describe the intensity and phase between different polarizations.

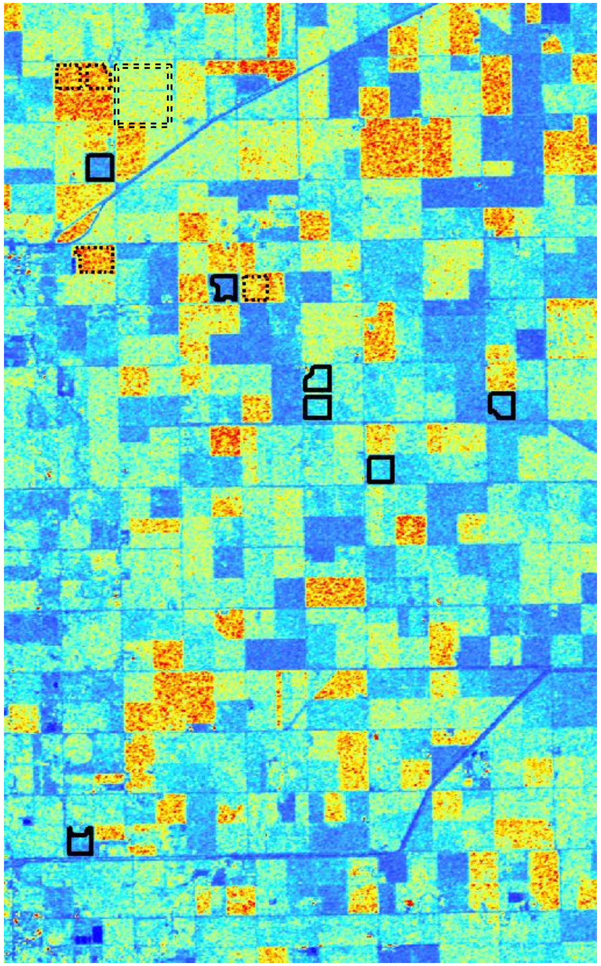


<u>Pauli (P) Scattering Vector</u>

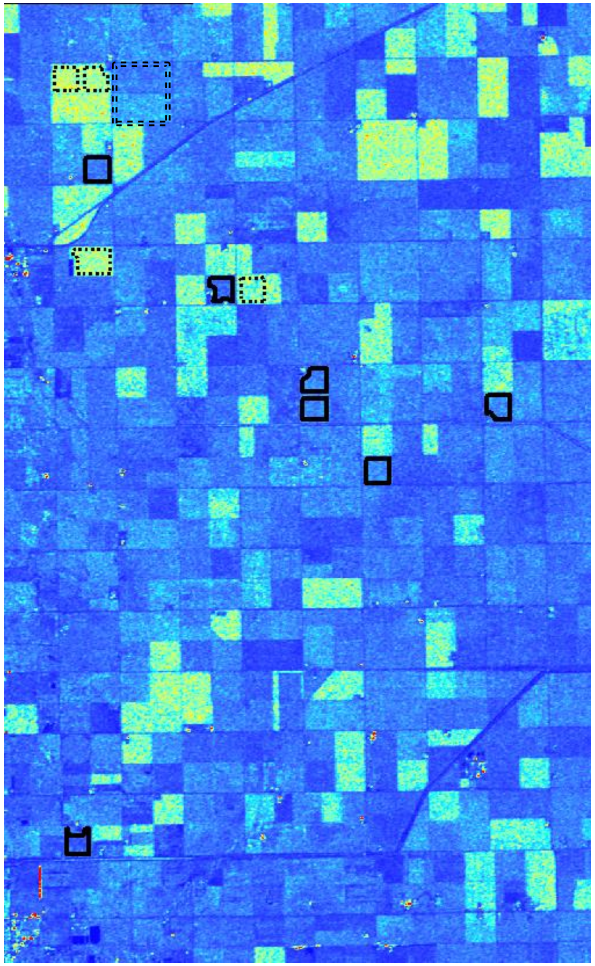
$$[T]=\frac{1}{2}\begin{bmatrix} S_{HH}+S_{VV} \\ S_{HH}-S_{VV} \\ 2S_{XX} \end{bmatrix}\begin{bmatrix}(S_{HH}+S_{VV})^* & (S_{HH}-S_{VV})^* & 2S_{XX}^*\end{bmatrix}=\begin{bmatrix} T_{11} & T_{12} & T_{13} \\ T_{12}^* & T_{22} & T_{23} \\ T_{13}^* & T_{23}^* & T_{33} \end{bmatrix}$$

$$[T]=\frac{1}{2}\begin{bmatrix} |S_{HH}+S_{VV}|^2 & (S_{HH}+S_{VV})(S_{HH}-S_{VV})^* & 2(S_{HH}+S_{VV})S_{XX}^* \\ (S_{HH}+S_{VV})^*(S_{HH}-S_{VV}) & |S_{HH}-S_{VV}|^2 & 2(S_{HH}-S_{VV})S_{XX}^* \\ 2(S_{HH}+S_{VV})^*S_{XX} & 2(S_{HH}-S_{VV})^*S_{XX} & 4|S_{XX}|^2 \end{bmatrix}$$

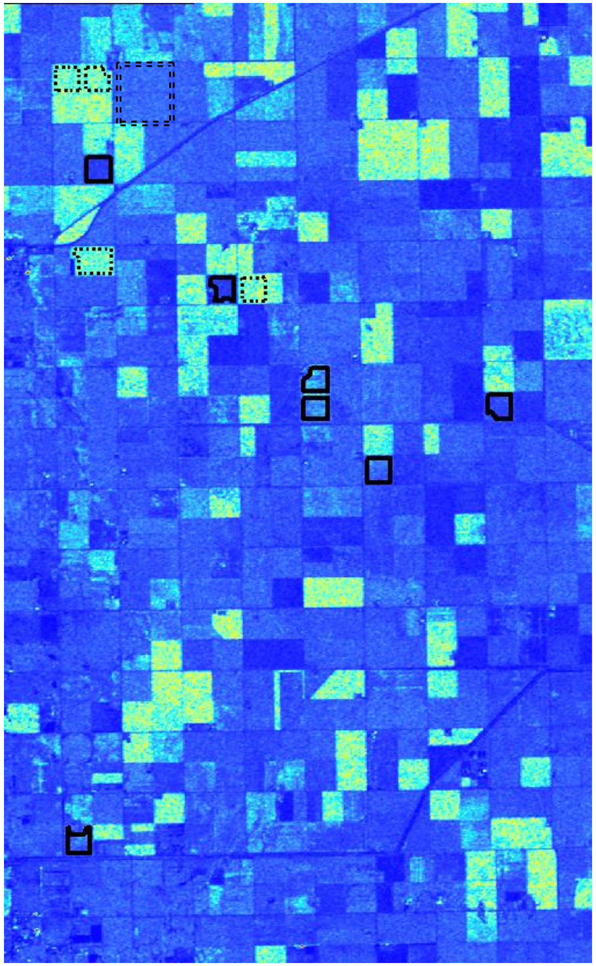
Coherency Matrix Elements



$T_{11} = 0.5|S_{HH} + S_{VV}|^2$



$T_{22} = 0.5|S_{HH} - S_{VV}|^2$



$T_{33} = 2|S_{XX}|^2$

Extracted from July 27th , 2016 RADARSAT-2 image

Decomposition Methods

- Decompositions allow the separation of different scattering contributions and can be used to describe the scattering properties (geometry and intensity) of the target.

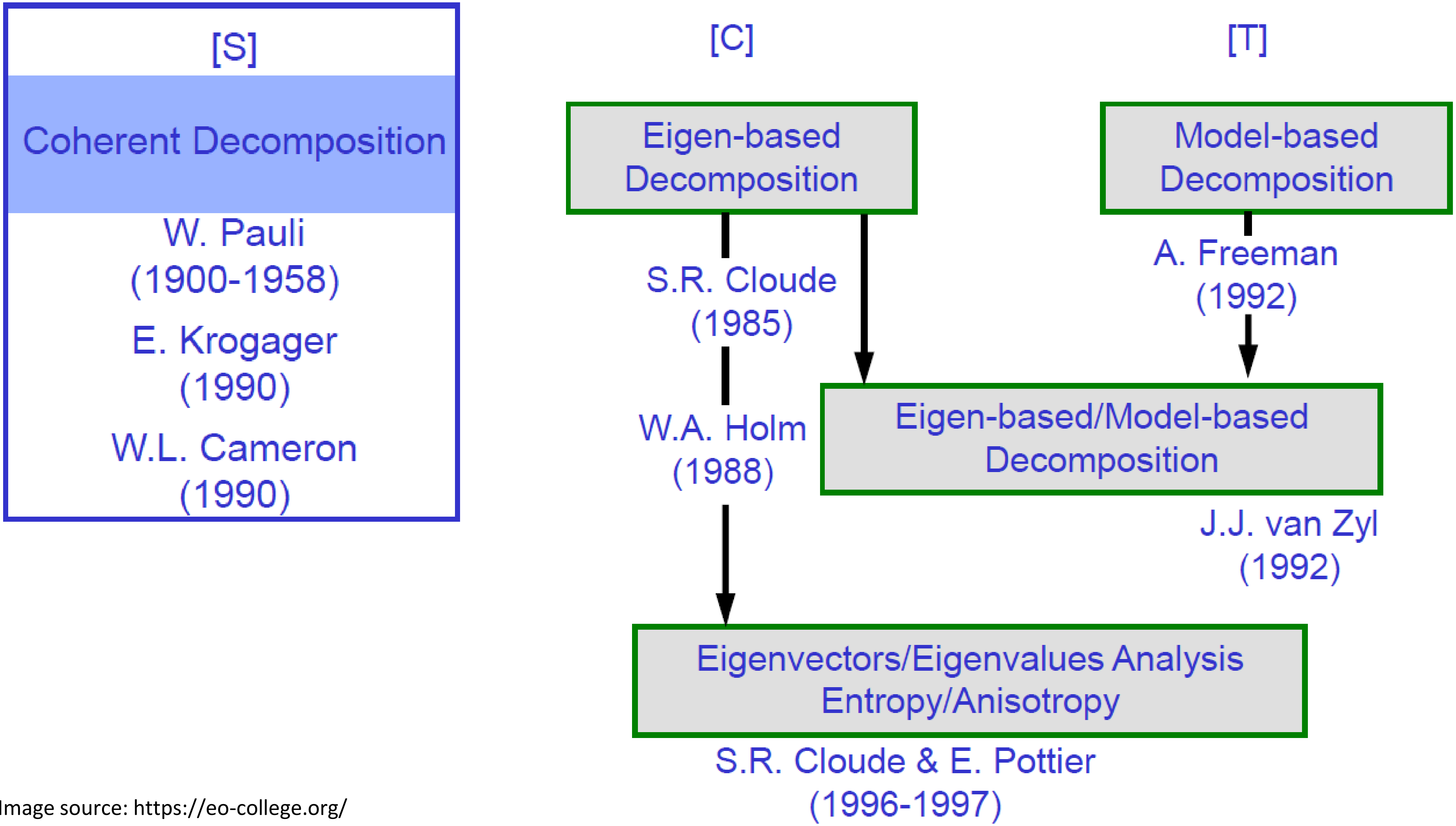


Image source: https://eo-college.org/

Coherent Decompositions

- The objective of the coherent decompositions is to express the measured **scattering matrix [*S*]**, as a the combination of different types of scatterers.
- Coherent decompositions are applied to coherent targets where the phase is known and predictable like **urban areas, calm water or manmade objects**.
- A direct analysis of the matrix [S] is very difficult to interpret.
- The physical properties of the target under study are extracted and interpreted through the analysis of the simpler responses $[S]_i$ and the corresponding coefficients.

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

where c_i indicates the weight of $[S]_i$ and k is the number of scattering types.

Pauli Decomposition

$$[S]_a = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad [S]_b = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \quad [S]_c = \frac{1}{\sqrt{2}}\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \quad [S]_d = \frac{1}{\sqrt{2}}\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

Reciprocity Condition

$$[S] = \begin{bmatrix} S_{hh} & S_{hv} \\ S_{hv} & S_{vv} \end{bmatrix} = \alpha [S]_a + \beta [S]_b + \gamma [S]_c$$

$$\alpha = \frac{S_{hh} + S_{vv}}{\sqrt{2}}$$

$$\beta = \frac{S_{hh} - S_{vv}}{\sqrt{2}}$$

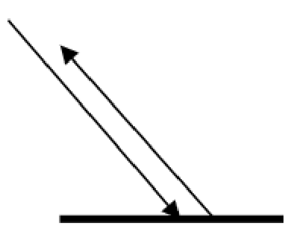
$$\gamma = \sqrt{2} S_{hv}$$

Pauli Decomposition

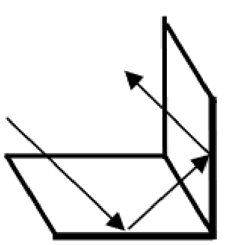
$$[S] = \begin{bmatrix} S_{hh} & S_{hv} \\ S_{hv} & S_{vv} \end{bmatrix}$$

$$= \frac{\alpha}{\sqrt{2}}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + \frac{\beta}{\sqrt{2}}\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} + \frac{\gamma}{\sqrt{2}}\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

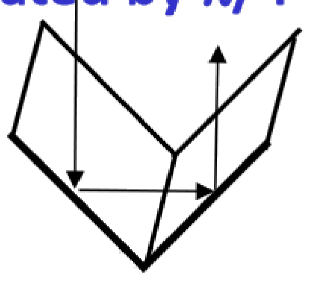
Single or odd-bounce scattering



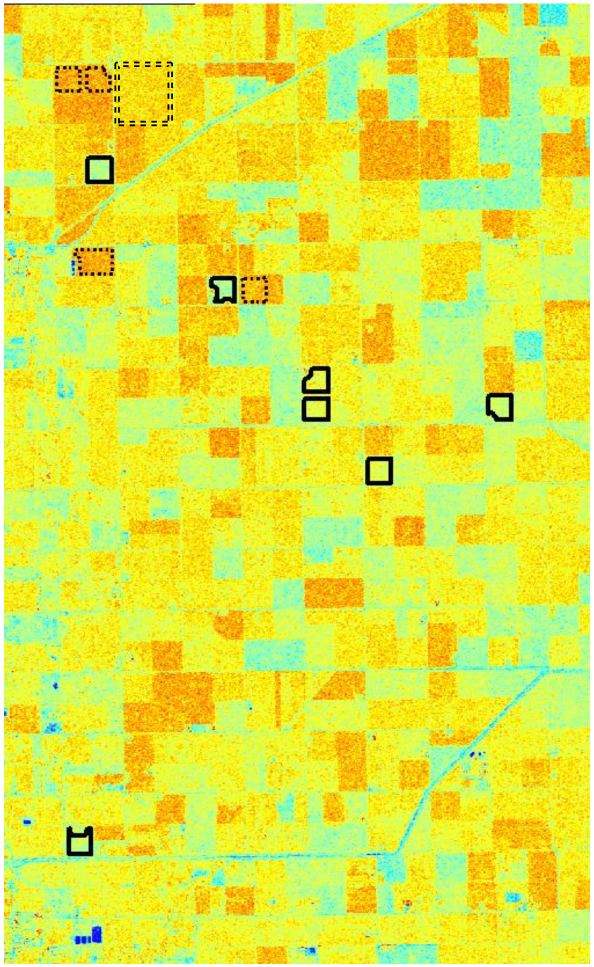
Dihedral or even-bounce scattering



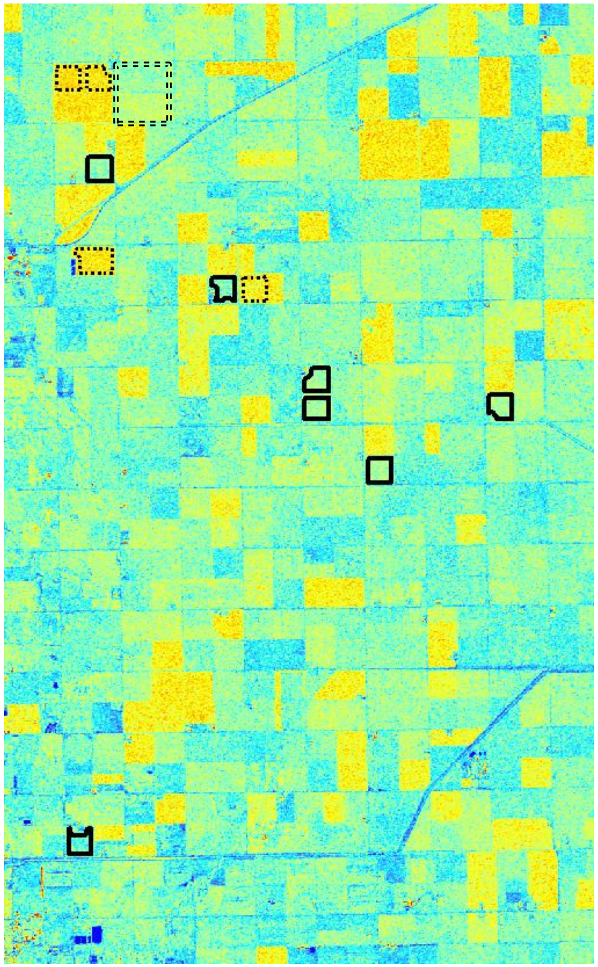
Dihedral or even-bounce scattering rotated by $\pi/4$



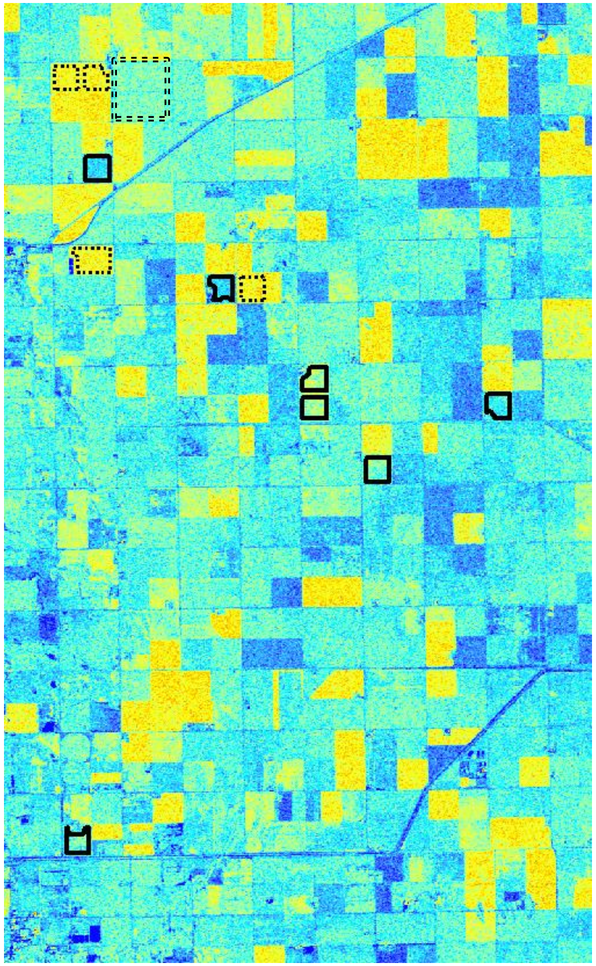
Pauli Decomposition (Intensities)



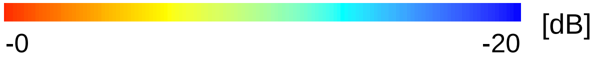
$|S_{HH} + S_{VV}|$



$|S_{HH} - S_{VV}|$

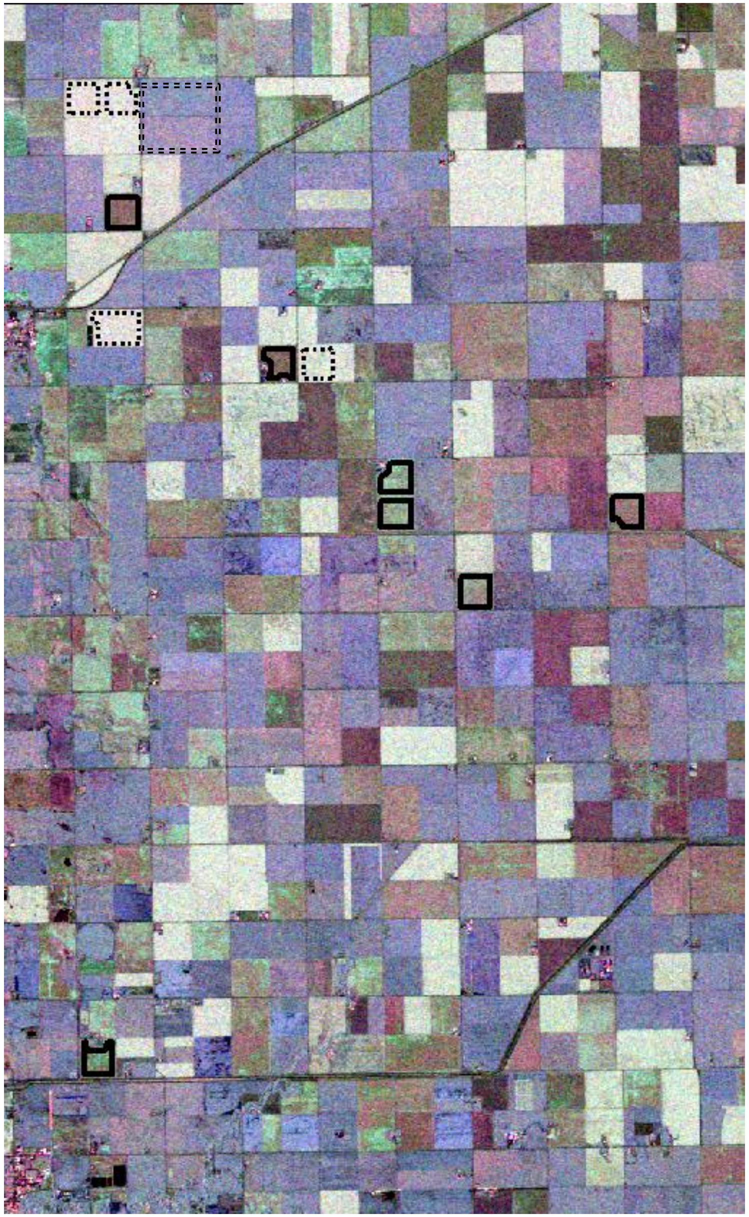


$2|S_{HV}|$



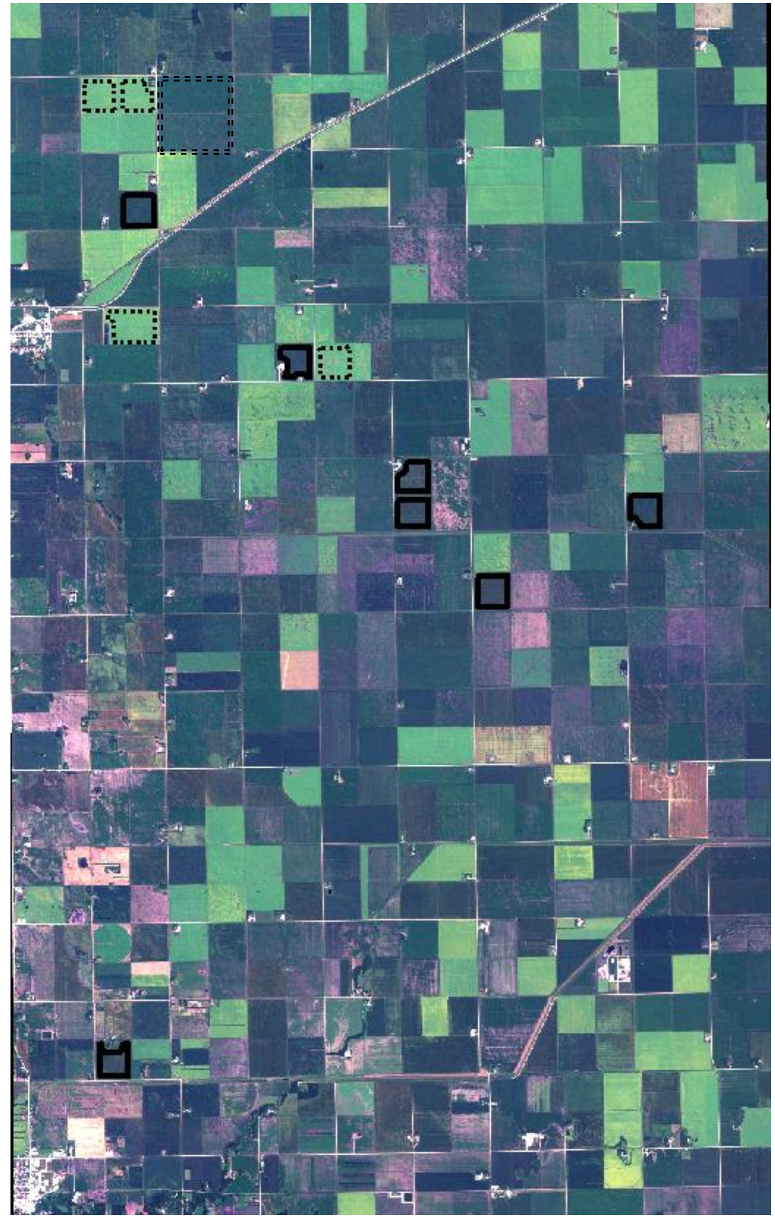
Extracted from July 27th, 2016 RADARSAT-2 image

Pauli Decomposition (Intensities): Comparison to Optical Image



$[S_{HH} + S_{VV}]$ $[S_{HH} - S_{VV}]$ $2[S_{HV}]$

Extracted from July 27th, 2016 RADARSAT-2 image



RapidEye optical image acquired on July 27th, 2016 (True color composite)

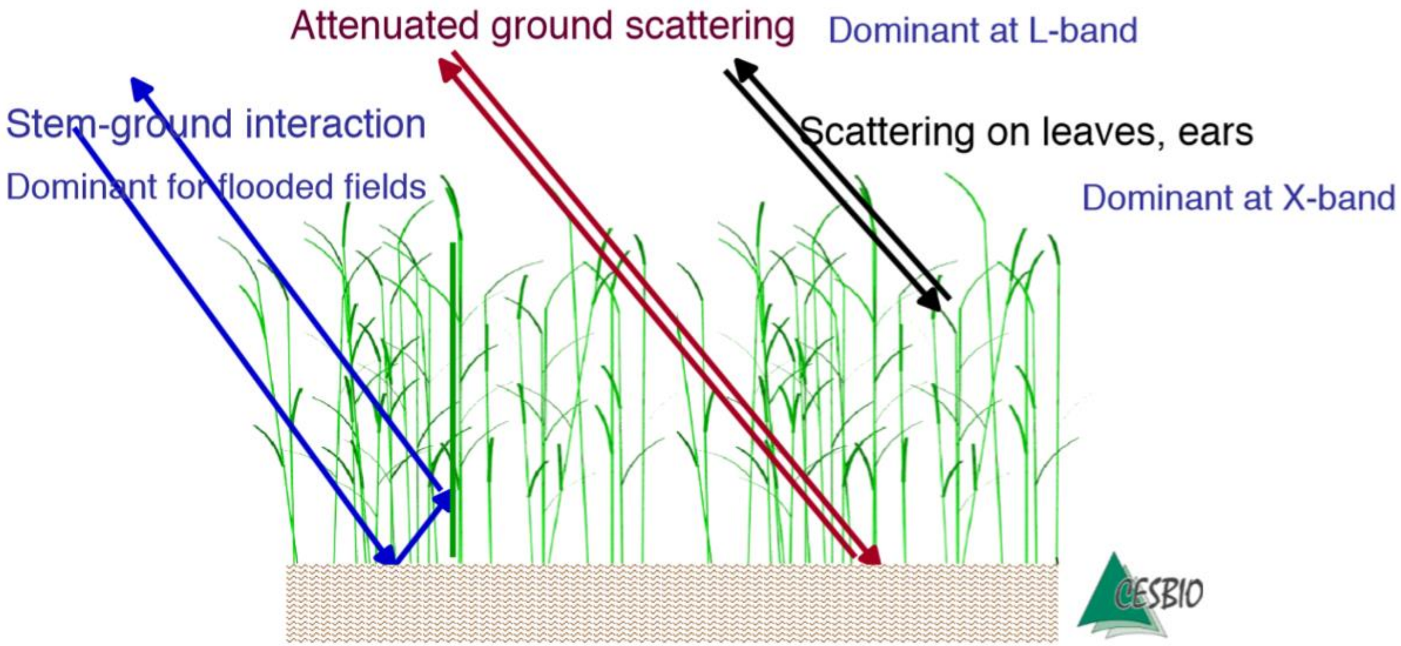
Incoherent Decompositions

- The incoherent decomposition polarimetric representations can be employed to analyze distributed scatterers.
- Incoherent decompositions are applied to incoherent targets where the phase is unknown and random like **agriculture, forest or rough water**.
- The second order descriptors are the 3×3, **covariance $[C]_3$** and the **coherency $[T]_3$** matrices.

$$\langle [C_3] \rangle = \sum_{i=1}^{k} p_i [C_3]$$

$$\langle [T_3] \rangle = \sum_{i=1}^{k} q_i [T_3]_i$$

where p_i and q_i indicate the weight of $[C_3]_i$ and $[T_3]_i$ and k is the number of scattering types.

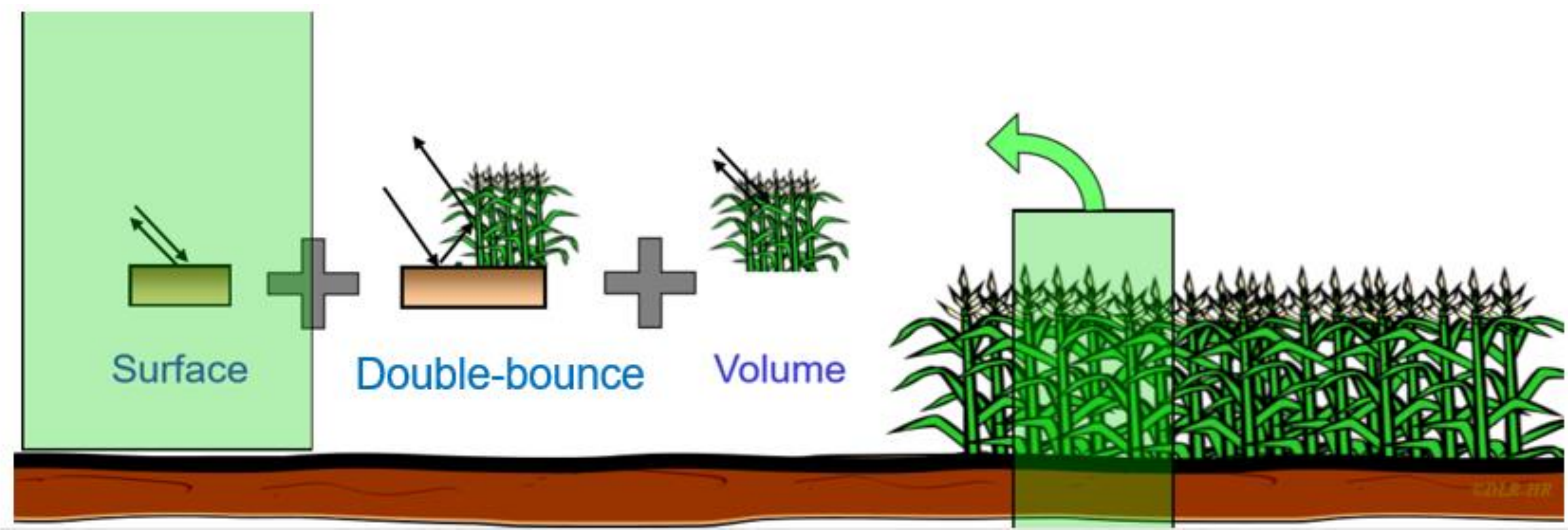


Freeman-Durden Decomposition

- This decomposition models the coherency matrix as the contribution of surface or single-bounce scattering, double-bounce and volume scattering mechanisms:

Total Scattering = Surface Scattering + Double-bounce + Volume Scattering

$$[T] = [T_s] + [T_D] + [T_V]$$

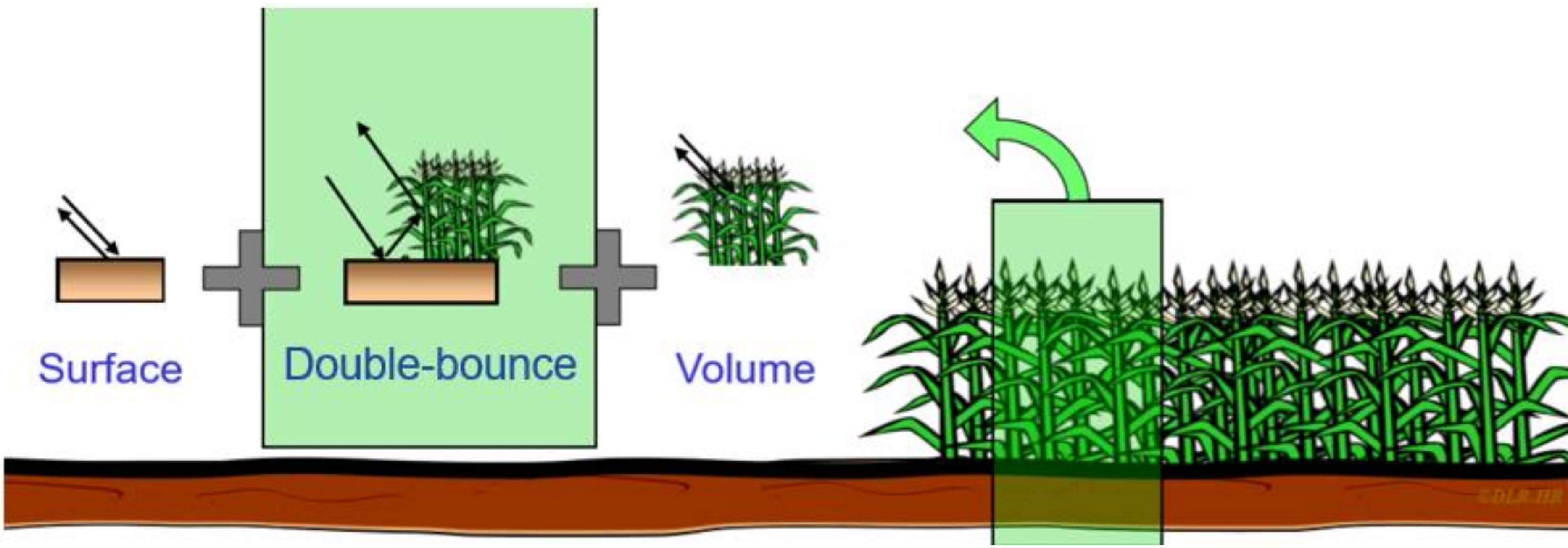


Freeman-Durden Decomposition

- This decomposition models the coherence matrix as the contribution of volume scattering, double-bounce and surface or single-bounce scattering mechanisms:

Total Scattering = Surface Scattering + Double-bounce + Volume Scattering

$$[T] = [T_s] + [T_D] + [T_V]$$



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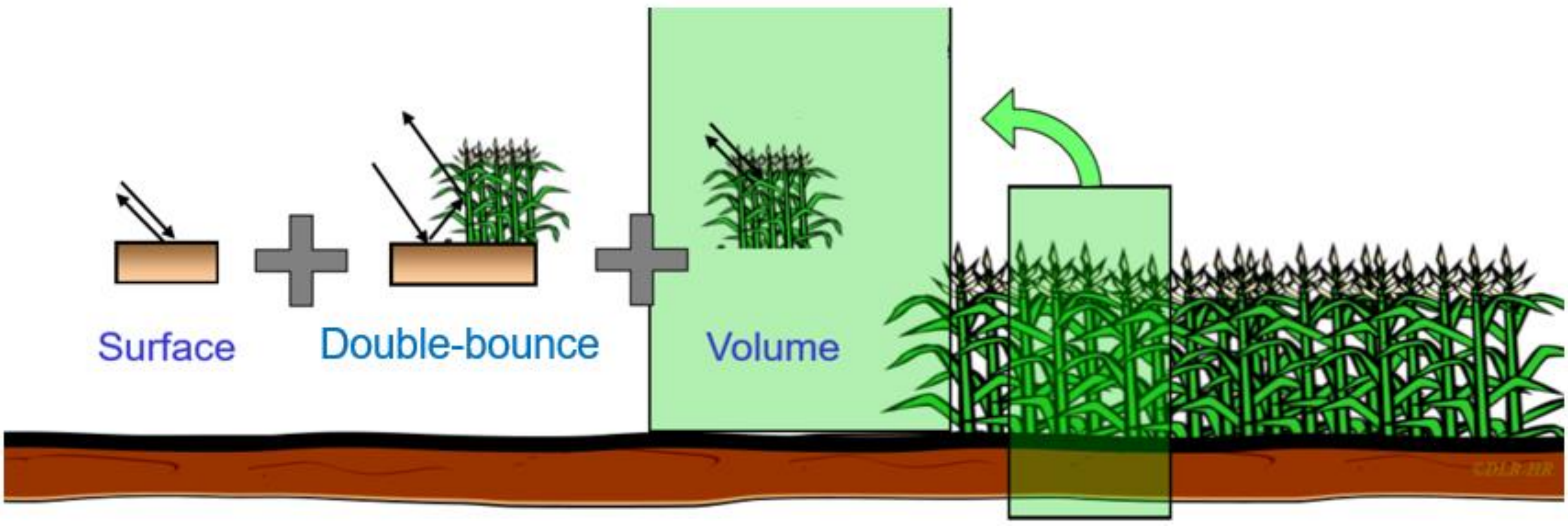
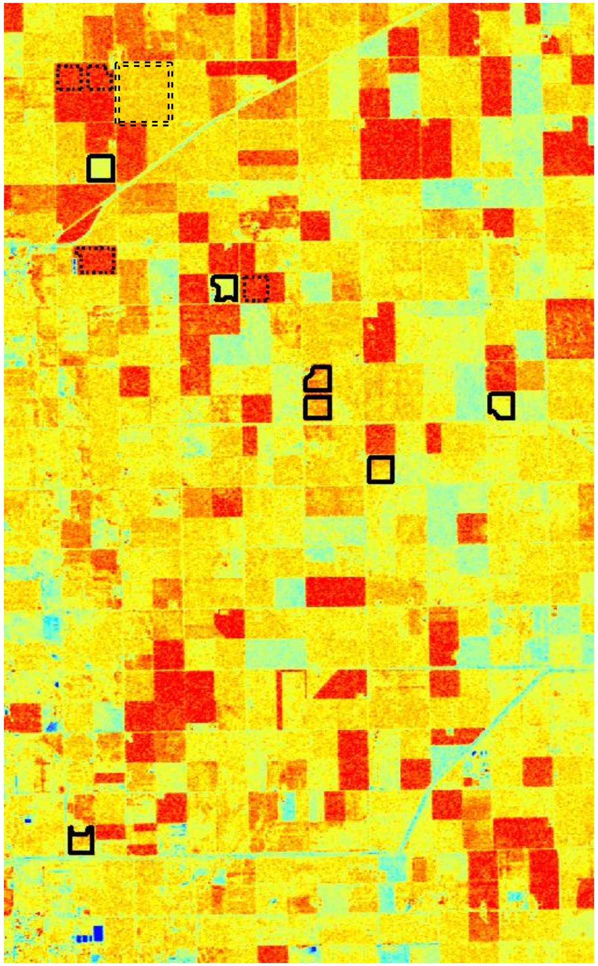
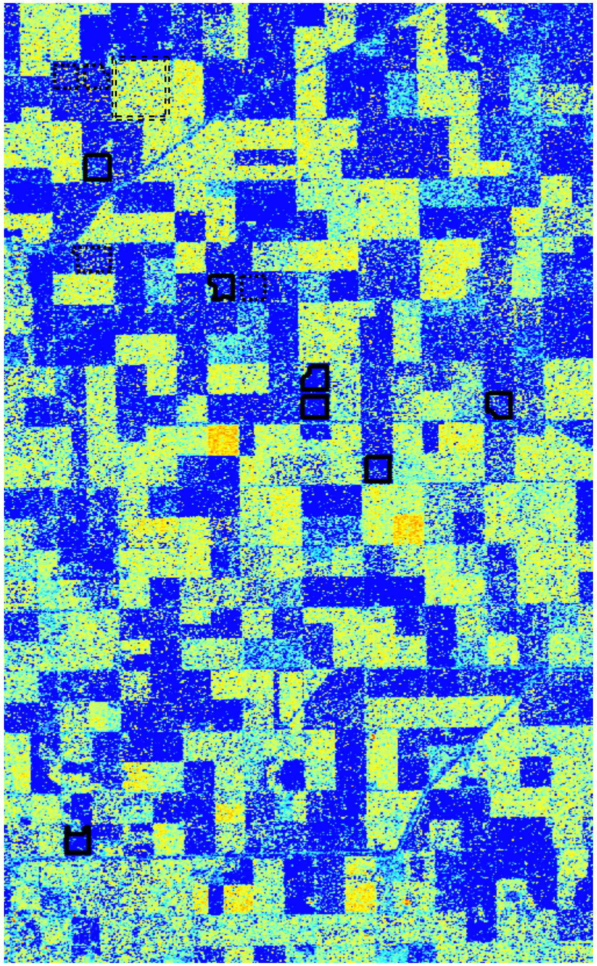


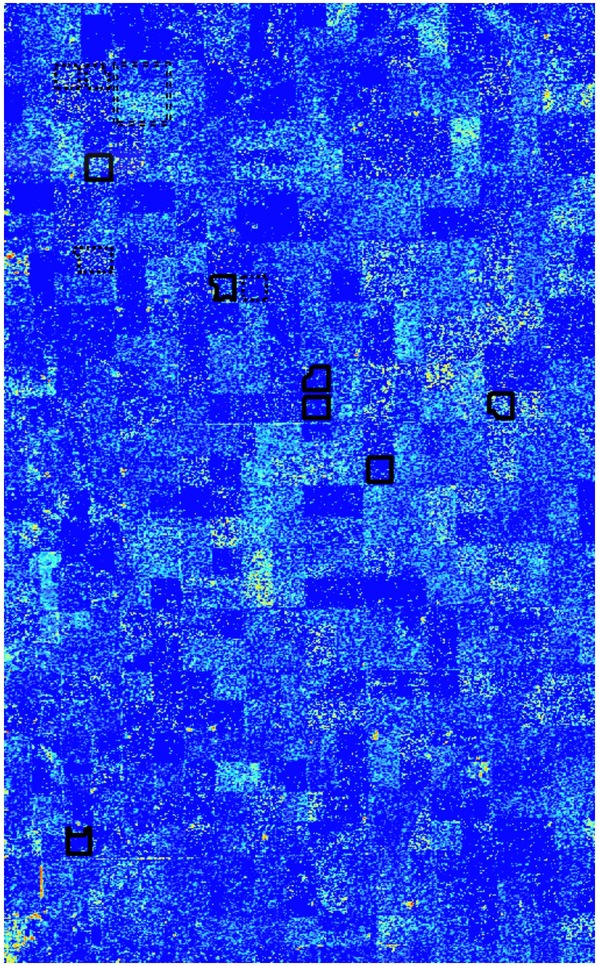
Freeman-Durden Decomposition



Volume scattering



Single scattering



Double scattering

Extracted from July 27th , 2016 RADARSAT-2 image

Eigen-Based Decomposition

Diagonalized Coherency Matrix

$$[T]=[U]\begin{bmatrix}\lambda_1 & 0 & 0\\ 0 & \lambda_2 & 0\\ 0 & 0 & \lambda_3\end{bmatrix}[U]^{-1}=\begin{bmatrix}\underline{u}_1 & \underline{u}_2 & \underline{u}_3\end{bmatrix}\begin{bmatrix}\lambda_1 & 0 & 0\\ 0 & \lambda_2 & 0\\ 0 & 0 & \lambda_3\end{bmatrix}\begin{bmatrix}\underline{u}_1 & \underline{u}_2 & \underline{u}_3\end{bmatrix}^{T*}$$

$\underline{u}_i$ = i^{th} eigenvector λ_i = i^{th} eigenvalue

Three Scattering Components

$$[T]=\lambda_1[T_1]+\lambda_2[T_2]+\lambda_3[T_3]$$

Entropy (H): The Degree of Randomness

Weighted Eigen Values

$$P_i = \lambda_i \Big/ \sum_{k=1}^{3} \lambda_k$$

Entropy (H)

$0 \leq H \leq 1$

$$H = -\sum_{i=1}^{3} P_i \log_3(P_i)$$

Coherent Target
(totally polarized)

$$\lambda_1 \approx 1 \quad \lambda_2 = \lambda_3 \approx 0 \Rightarrow H = 0$$

Randomly Distributed Target
(totally unpolarized)

$$\lambda_1 = \lambda_2 = \lambda_3 = SPAN/3 \Rightarrow H = 1$$

Anisotropy (A): The Impact of Secondary Scattering Mechanisms

Anisotropy (A)

$0 \leq A \leq 1$

$$A = \frac{\lambda_2 - \lambda_3}{\lambda_2 + \lambda_3} = \frac{P_2 - P_3}{P_2 + P_3}$$

Only one secondary scattering mechanism

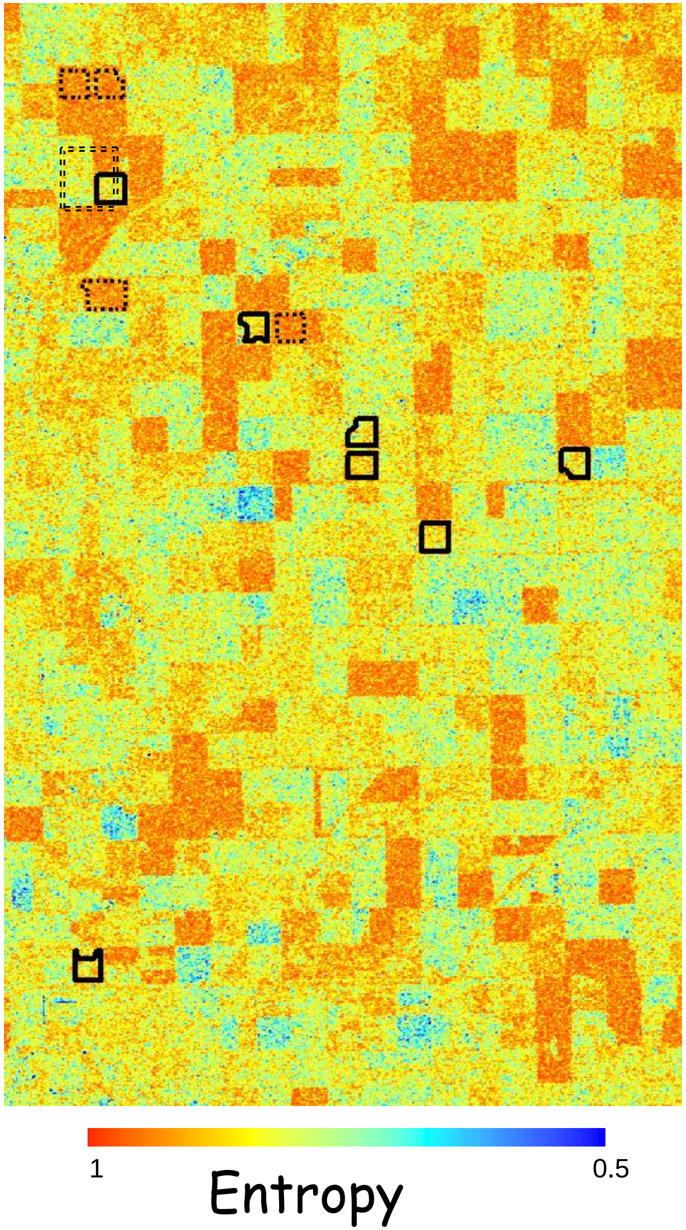
$\lambda_2 \approx 1 \quad \lambda_3 \approx 0 \Rightarrow A = 1$

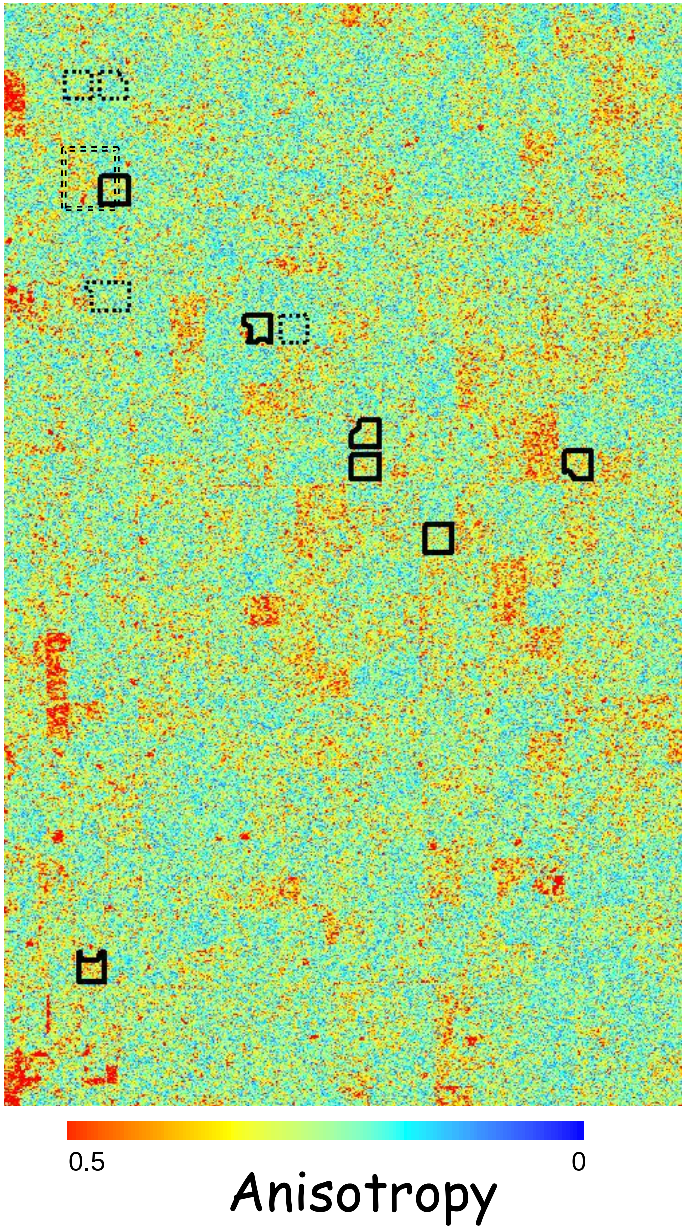
Two equal scattering mechanisms

$\lambda_2 \approx \lambda_3 \Rightarrow A = 0$

Distributed targets (such as cropped fields): Usually one mechanism dominates, but other (secondary and possibly tertiary) mechanisms are present.

Entropy and Anisotropy





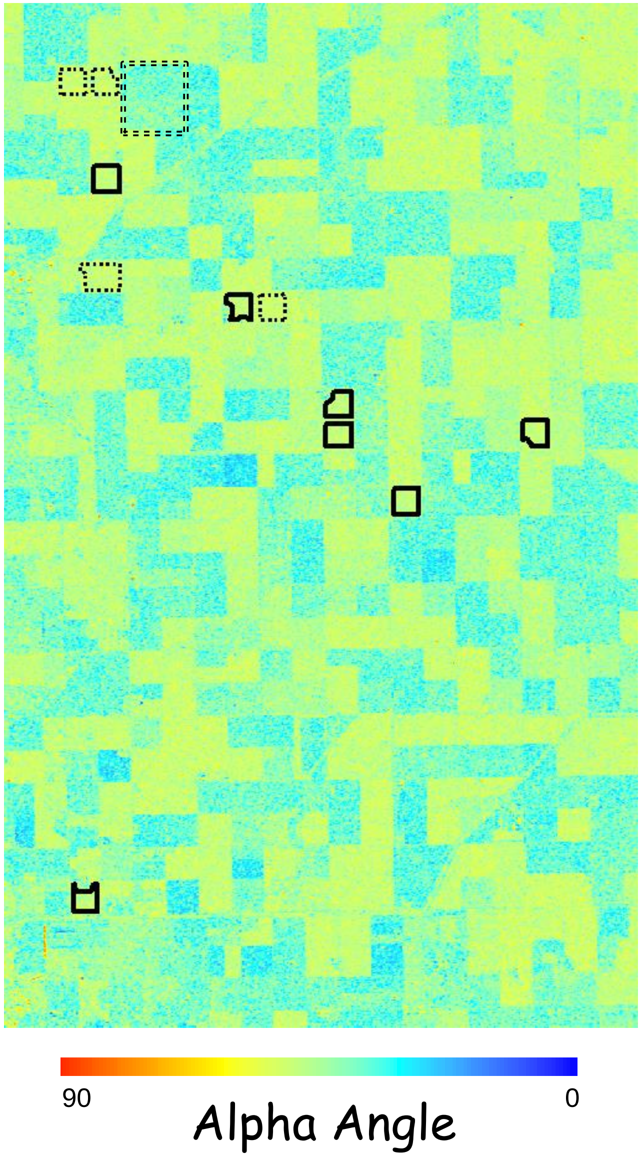
Extracted from July 27th , 2016 RADARSAT-2 image

Average Alpha Angle ($\bar{\alpha}$): The Dominate Scattering Mechanism

$$\bar{\alpha} = P_1\alpha_1 + P_2\alpha_2 + P_3\alpha_3$$

$$0 \le \bar{\alpha} \le 90^o$$

0° = single-bounce
45° = multiple/volume
90° = double-bounce



What does this mean for agriculture

0° = single scattering event from smooth soil or large leaf

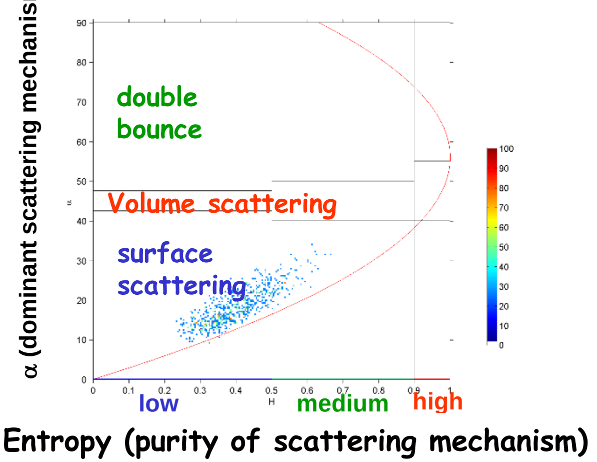
45° = multiple (more than two) scattering events from within a crop canopy

90° = two scattering events from a large stalk and the soil

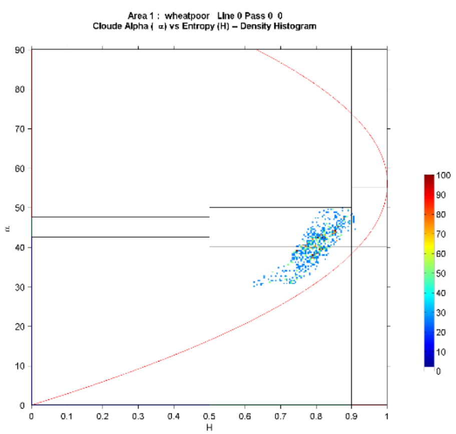
Sources of Scattering as a Function of Incidence Angle

Cloude-Pottier Scattering Plots

Wheat



Incidence angle – 25°

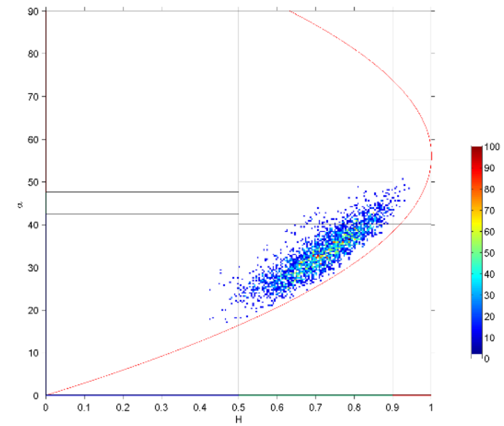


Incidence angle – 45°

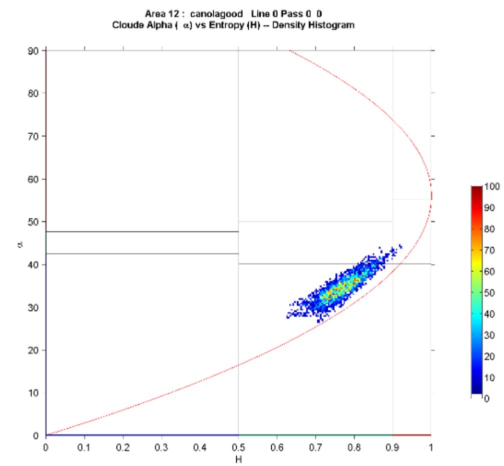
Alpha angle (α): defines the dominant source of scattering. Values range from 0° to 90°, $\alpha = 0$ indicates single-bounce scattering, $\alpha \approx 45°$ represents double-bounce scattering, and $\alpha \approx 90°$ characterizes dominant volume scattering

Entropy (H): determines the randomness of the scattering mechanism. Low entropy ($H = 0$) indicates the backscattering mechanism is fully polarized while high entropy ($H = 1$) indicates the backscattering mechanism is fully un-polarized (phase from one resolution element to another in target is not predictable)

Canola



Incidence angle – 25°

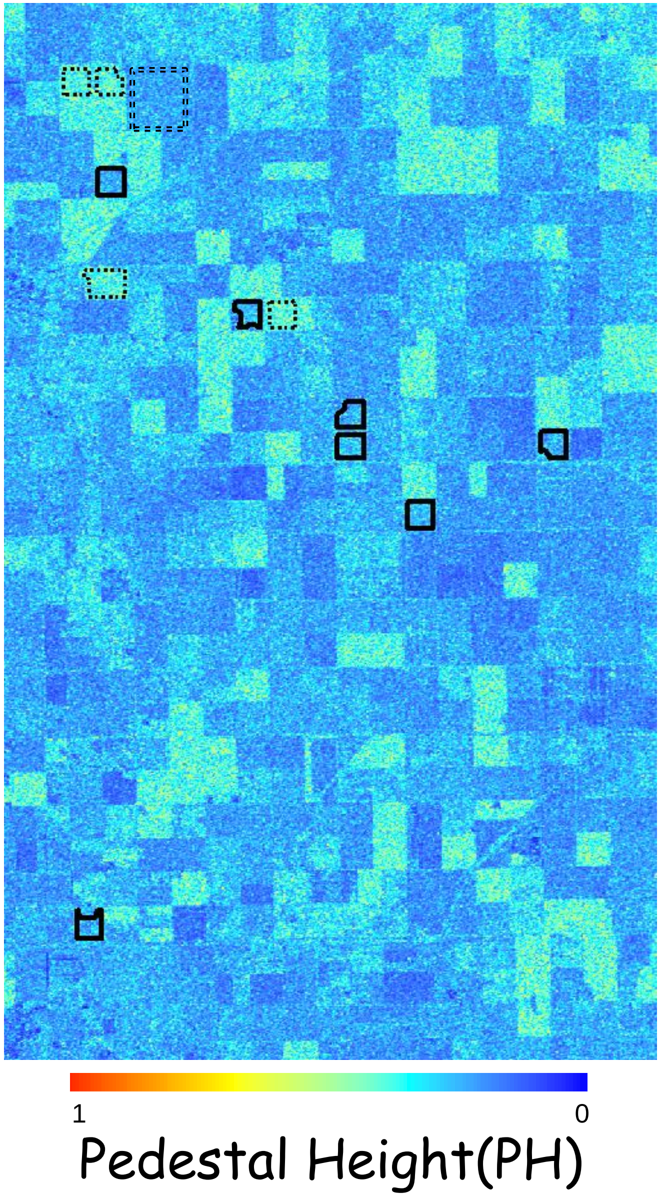


Incidence angle – 45°

Pedestal Height (PH): Measure of Randomness in Scattering

$$PH = \frac{\min(\lambda_1, \lambda_2, \lambda_3)}{\max(\lambda_1, \lambda_2, \lambda_3)} = \frac{\lambda_3}{\lambda_1}$$

$$0 \le PH \le 1$$



Extracted from July 27th, 2016 RADARSAT-2 image

Measure of randomness in the scattering process = Strength of the unpolarized power

0 = Not random

1 = Totally random

Compact Polarimetry

But Why? Remember what we learned.

- Fully polarimetry SARs require twice the pulse repetition frequency (data rate) and power usage of a dual-pol SAR
- To keep power usage constant fully polarimetric modes have half the swath width

Compact Polarimetry (CP)

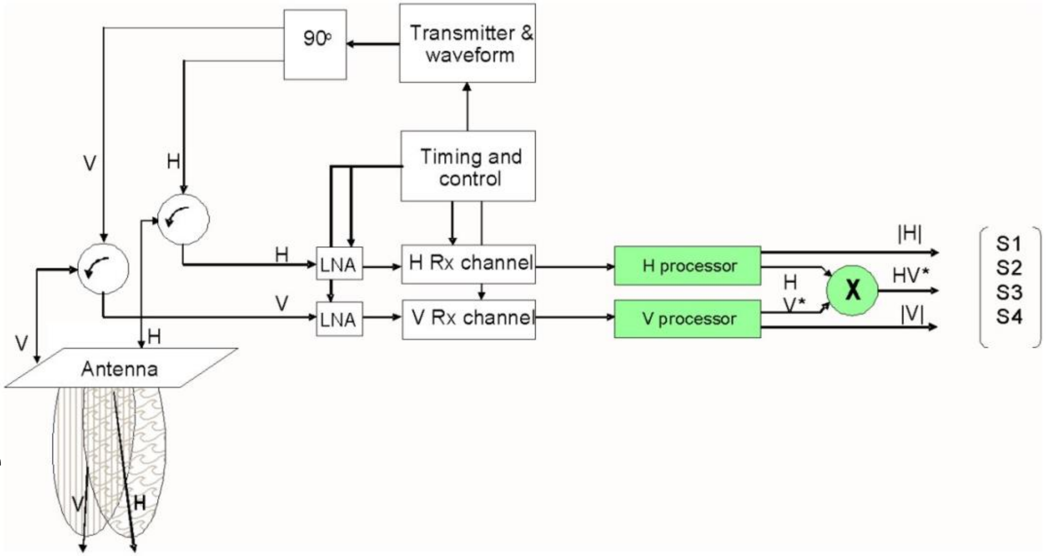
- CP can be implemented for wide swaths (hundreds of km, for example) and is thus of significant interest for application to regional and national monitoring

Compact Polarimetry: How Does It Work?

• only one polarization is transmitted; two orthogonal polarizations are received and relative phase between two receive polarizations is retained

Many options for CP*
• transmit H or V and receive H & V coherently (results have not been promising)
• transmit linearly-polarized field at 45° then receive coherently H & V (appropriate only for scatterers whose orientation distributions are predominantly horizontal or vertical)
• transmit and receive circular (CC) (awkward to implement)

*Dr. Keith Raney, Johns Hopkins University



Hybrid-polarity (Circular-Linear or CL) is a preferred option
• H & V transmitted simultaneously & 90° out of phase; dual receive linearly-polarized antenna

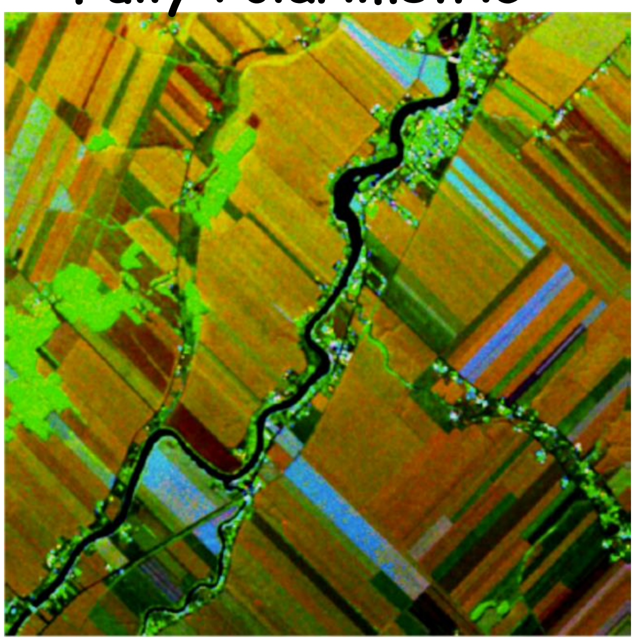
Compact Pol (CP) Data

- Research has been conducted on CP data, primarily simulated from fully polarimetric data
- Although CP data can synthesize parameters similar to those from QP, the scientific community is still assessing the performance of CP for applications. However in general the information content is as follows:

QP > CP > dual polarizations

- Several satellites have or will have a CP option (ALOS-2, RISAT-1, SAOCOM, RCM, NISAR)

Fully Polarimetric



Simulated Compact-Pol

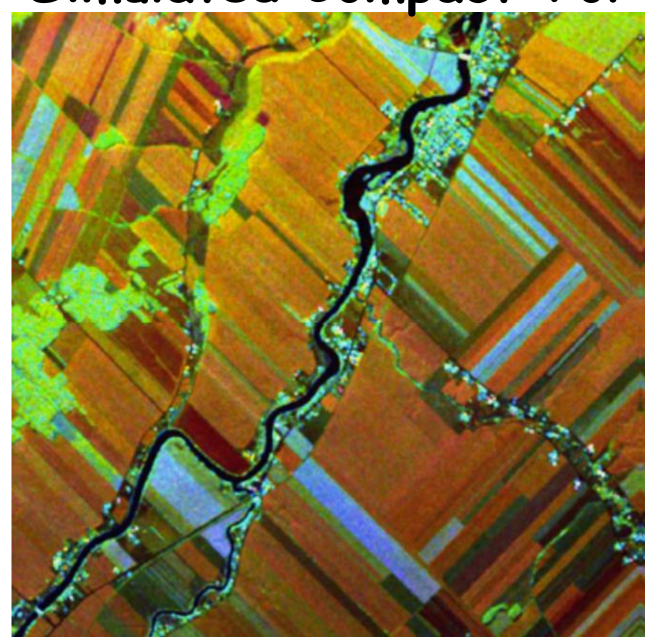


Image source: Dr. Francois Charbonneau

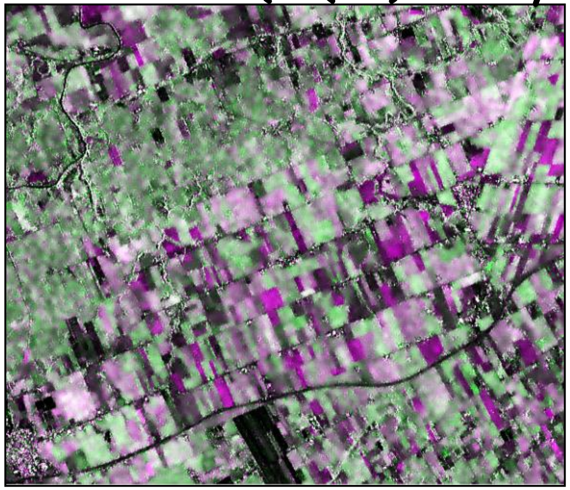
RGB composite based on scattering mechanisms:
Red: Double bounce; Green: Volume; Blue: Surface scattering

Compact Pol (CP) Output Parameters

Parameters	Interpretation
Stokes vector for right circular transmitting system (RCM-CP mode) $$\begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} \langle \lvert RH \rvert^2 + \lvert RV \rvert^2 \rangle \\ \langle \lvert RH \rvert^2 - \lvert RV \rvert^2 \rangle \\ 2\,\mathrm{Re}\langle RH \cdot RV^* \rangle \\ -2\,\mathrm{Im}\langle RH \cdot RV^* \rangle \end{bmatrix} = \begin{bmatrix} \langle \lvert RR \rvert^2 + \lvert RL \rvert^2 \rangle \\ \langle \lvert RR \rvert^2 - \lvert RL \rvert^2 \rangle \\ 2\,\mathrm{Re}\langle RR \cdot RL^* \rangle \\ -2\,\mathrm{Im}\langle RR \cdot RL^* \rangle \end{bmatrix} = S_0 \begin{bmatrix} 1 \\ \cos(2\psi)\cos(2\chi) \\ \sin(2\psi)\cos(2\chi) \\ \sin(2\chi) \end{bmatrix}$$	**Stokes vectors** S_o : sum of the two receiving channels (total power received) S_1 : intensity difference between RR and RL S_2 and S_3 : info about the relative phase between the two receiving channel S_3 : info on the ellipticity of the wave
Ellipticity $\boldsymbol{\mu}_E = S_3 / S_0$	**Ellipticity** How circular is the receiving wave μ_E = 0 : linear μ_E = -1 : Right circular (double bounce scattering where RR>>RL) μ_E = +1 : Left circular (surface scattering where RL>>RR)
Circular polarization ratio $\boldsymbol{\mu}_C = (S_0 - S_3) / (S_0 + S_3)$	**Circular polarization ratio** How circular is the receiving wave and what is the sense of the rotation (left or right) μ_C = 1 : linear μ_C = 0 : left circular μ_C >>1 : right circular
m **-*δ* Feature Decomposition** dominantly depolarised (volume) backscatter dominantly double bounce backscatter dominantly single bounce backscatter	***m*** **-*δ* Feature Decomposition** ***m*** : degree of polarization ***δ*** : relative phase between two received polarizations (RH and RV)

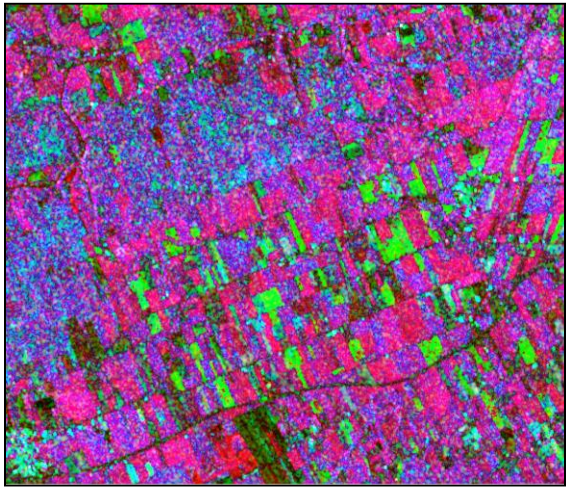
How Does Compact Pol (CP) Perform?

RADARSAT-2 (FQ19) - July 16 2008

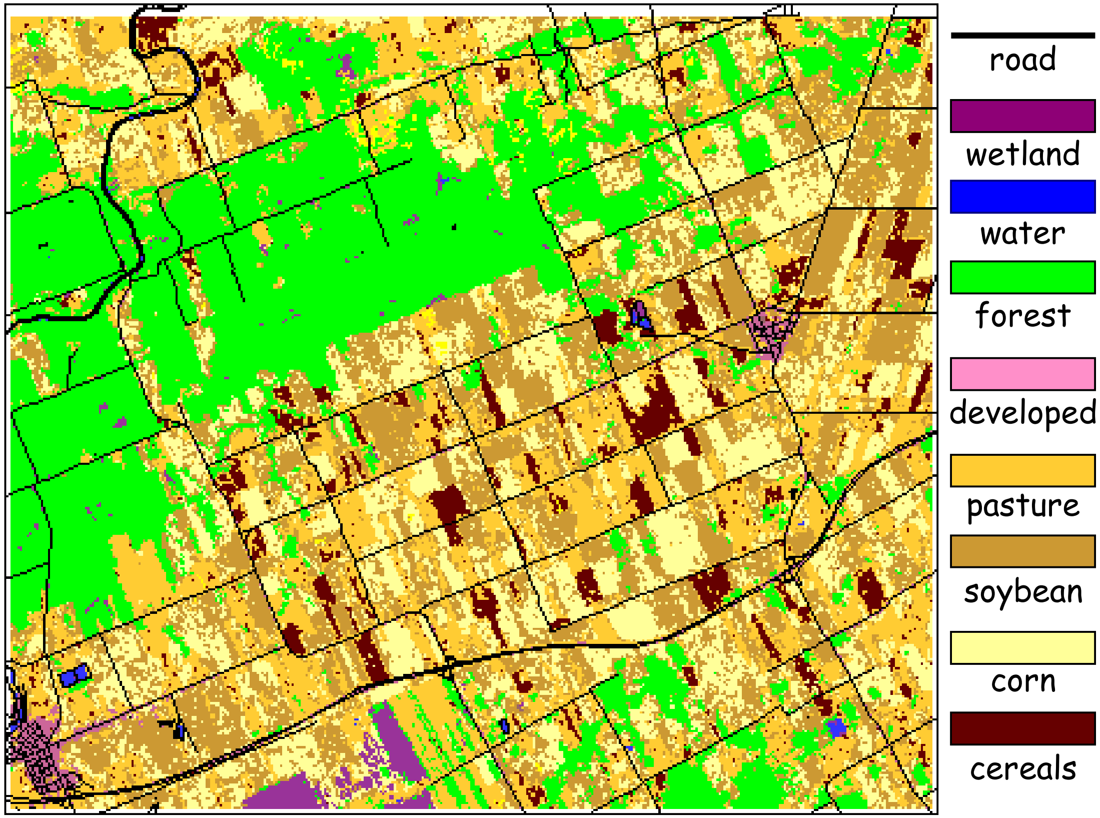


HH, VV, HV

mDelta Decomposition From Simulated CP



mDelta single, double, volume



Classification generated from mDelta
84.3% overall accuracy