Amplitude of the Electric field is given by:

\[ E(z,t) = E_0 \sin(\omega t - kz + \phi_0) \]

\[ = E_0 e^{j(\omega t + \phi)} \]

Wave Polarization

Types of Polarization

Pol-SAR vs Multi-spectral Optical Data
The scattering matrix, Stokes matrix and polarization signature can be computed for each pixel:

- can be a powerful classification tool
- for both visual and machine classification

The scattering matrix can be used:
- to synthesize the return with any transmit/receive polarizations
- to investigate the scattering properties of different surfaces
- to optimize polarization for optimum detectability

**Data:**
- L-band SAR (ALOS-PALSAR-2) data of Mumbai; DoA:

**RADARSAT-2**
- C-band
- Dec 14, 2007

**ALOS-PALSAR**
- L-band
- May 24, 2014
**Radar Basics: Single-Look Complex (SLC) Data**

- 4 complex numbers corresponding to each radar resolution cell (pixel), one each for HH, HV, VV and HH polarization channels.
- Each complex number is stored in 2 real numbers; one represents the "Real" part (I) and the other represents the "Imaginary" part (Q).
- The amplitude (magnitude) of each polarization is obtained as:
  \[ A = \sqrt{I^2 + Q^2} \]
- The phase (absolute) of each polarization is obtained as:
  \[ \phi = \tan^{-1}(Q/I) \]

**Radar Basics: Multi-Look Averaging**

- The magnitude of a sum of complex numbers (voltages) gives a Rayleigh distribution.
- The magnitude of a square of a sum of complex number (power \( \rightarrow \) RCS & NRCS) is an exponential distribution.
- When trying to estimate the RCS or NRCS, these statistics are treated as noise.
- To reduce the noise, we can perform multi-look averaging.

**Radar Basics: Amplitude, Intensity, Phase**

- Intensity = (Amplitude)^2
- It is a measure of the reflective strength of a radar target.
- The complex envelope of the radar return from a distributed target is what the background color of the multi-look data reflects. It is defined as the sum of the amplitudes:
  \[ A^2 = \beta^2 \times \sin \theta \]
  \[ \gamma^2 = \beta^2 \times \tan \theta = \sigma^2 \times \cos \theta \]

**Absolute and Relative Phase (APD or FPD):**

The phase of the dual wave is used to provide a reference for timing with respect to a common point in phase space.

\[ \phi_{rel} = \tan^{-1} \left( \frac{\Delta \text{dim}_1}{\Delta \text{dim}_2} \right) = \tan^{-1} \left( \frac{\text{dim}_1}{\text{dim}_2} \right) \]
Sources of scattering within a volume:

- Number density
- Size relative to wavelength
- Dielectric contrast
- Shape and orientation

Backscatter intensity and relative phase over natural targets:

<table>
<thead>
<tr>
<th>Example</th>
<th>Odd-bounce/Bragg Scattering</th>
<th>Volume Scatterer</th>
<th>Even-bounce Scatterer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth bare field, water</td>
<td>Low VV &gt; HH &gt;&gt; HV</td>
<td>Medium HH ≈ VV &gt; HV</td>
<td>High HH &gt; VV &gt;&gt; HV</td>
</tr>
<tr>
<td>Crops, tree-canyon, dry snow, sand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buildings, bridges, electric poles, etc.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Surface Double Bounce
Distributed thin dipole

Bragg Scattering

Relative Phase

0° - 90° - 180°

Example:
- Smooth bare field, water
- Crops, tree-canyon, dry snow, sand
- Buildings, bridges, electric poles, etc.

SAR SLC Image
Backscatter Coefficient Image (σ0)

Incidence Angle Image (θ)

Sensor parameters

Image Ortho-rectification

Ortho-rectified image

Ortho-rectified incidence angle image

Local incidence angle image

Slope (β)
Aspect (A)
Flight Geometry (T)

Terrain Corrected Images

Slope (S)
Aspect (A)
Flight Direction (T)

SAR Intensity Image

Monostatic Imaging

Bistatic Imaging

Standard Conventions used in SAR Polarimetry

Monostatic and Bistatic Radar

Monostatic Imaging

Bistatic Imaging
Back Scattering Alignment (BSA) Forward Scattering Alignment (FSA)

For Radar remote sensing a more comprehensive term: Monostatic Scattering Alignment Condition the Symmetrization of Cross-Pol scattering matrix can be written as:

Due to propagation alone:

The scattering elements contain both phase and amplitude information. So scattering matrix can be written as:

For a linear full polarimetric system:

Covariance or Coherence matrix (higher order matrix)

Polarimetric system

Point Target vs Distributed Target

Point Targets

Target smaller than radar resolution cell

Distributed Targets

Target larger than radar resolution cell

No effect of surrounding pixels on the pixel with point target. The pixel can be fully characterized by a scattering matrix.

The pixel can not be fully characterized without taking into account surrounding pixels. Requires higher order matrix. Coherency or Covariance matrix [H] matrix:

For bistatic case:

For monostatic case:

The Radar Cross Section is the scattering capability of a target and is defined as:

Rotostatic case: total 12 (4 magnitude and 8 phases) independent quantities must be measured.

Monostatic case: only 7 (3 magnitude and 4 phases) independent quantities need to be measured.
Covariance Matrix

The covariance matrix is a means of expressing the properties of the received signal in the Power Domain as opposed to the Voltage Domain used in Scattering Matrices.

The covariance vector $K_e$ is a normalized version of the scattering matrix:

$$K_e = \begin{bmatrix} S_{rr} \\ S_{rl} \\ S_{lr} \\ S_{ll} \end{bmatrix}$$

Assuming reciprocity, i.e., $S_{lr} = S_{rl}$.

The power domain representation of the scattering properties is done by forming the product of this vector with itself. This results in the covariance matrix, which also fully describes the scattering properties of the target.

$$C = K_e \cdot K_e^T = \begin{bmatrix} S_{rr} & S_{rl} & S_{lr} & S_{ll} \\ S_{rl} & S_{rr} & S_{lr} & S_{ll} \\ S_{lr} & S_{lr} & S_{ll} & S_{rr} \\ S_{ll} & S_{ll} & S_{rl} & S_{rr} \end{bmatrix}$$

The Covariance vector $K_{cov}$ in Circular basis.

$$K_{cov} = \begin{bmatrix} S_{rr} \\ S_{rl} \\ S_{lr} \\ S_{ll} \end{bmatrix}$$

Assuming reciprocity, i.e., $S_{rl} = S_{lr}$.

The Covariance matrix in Circular basis:

$$C = K_{cov} \cdot K_{cov}^T = \begin{bmatrix} S_{rr}^2 & S_{rl}^2 & S_{lr}^2 & S_{ll}^2 \\ S_{rl}^2 & S_{rr}^2 & S_{lr}^2 & S_{ll}^2 \\ S_{lr}^2 & S_{lr}^2 & S_{ll}^2 & S_{rr}^2 \\ S_{ll}^2 & S_{ll}^2 & S_{lr}^2 & S_{rr}^2 \end{bmatrix}$$

Polarization Ellipse

- Indicates the sign of rotation of the ellipse and its ellipticity
- Orientation of the long axis of the polarization ellipse

The polarization ellipse, including the Poincaré variables $\rho$ and $\varphi$.

$S_1 = \rho \cos \psi + S_{ll} - S_{rr}$

$S_2 = \rho \sin \psi + S_{rl} - S_{lr}$

$S_3 = 2 \rho \cos \psi - 2 S_{ll}$

$S_4 = 2 \rho \sin \psi - 2 S_{rl}$

The four Stokes parameters of the partially polarized signal or the Poincaré sphere in the transmitted field.
Circular Polarimetry

\[ S_0 = \langle E_{x0}^t + E_{x0}^r \rangle \]
\[ S_1 = \langle E_{y0}^t - E_{y0}^r \rangle \]
\[ S_2 = 2\Re(\bar{E}_{x0}^t E_{x0}^r) \]
\[ S_3 = 2\Im(\bar{E}_{x0}^t E_{x0}^r) \]

Linear Polarimetry

\[ S_0 = \langle |E_{x0}^t|^2 + |E_{x0}^r|^2 \rangle \]
\[ S_1 = \langle |E_{y0}^t|^2 - |E_{y0}^r|^2 \rangle \]
\[ S_2 = 2\Re(\bar{E}_{x0}^t E_{x0}^r) \]
\[ S_3 = 2\Im(\bar{E}_{x0}^t E_{x0}^r) \]

Hybrid Polarimetry

\[ S_0 = \langle E_{x0}^t \rangle \]
\[ S_1 = \langle E_{y0}^t \rangle \]
\[ S_2 = 2\Re(\bar{E}_{x0}^t E_{x0}^r) \]
\[ S_3 = 2\Im(\bar{E}_{x0}^t E_{x0}^r) \]

Circular Polarimetry

\[ S_0 = \langle |E_{x0}^t|^2 + |E_{x0}^r|^2 \rangle \]
\[ S_1 = \langle |E_{y0}^t|^2 - |E_{y0}^r|^2 \rangle \]
\[ S_2 = 2\Re(\bar{E}_{x0}^t E_{x0}^r) \]
\[ S_3 = 2\Im(\bar{E}_{x0}^t E_{x0}^r) \]

Stokes' Vector

\[ \mathbf{S} = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} \]

Normalized Degree of Polarization:

\[ \rho = \frac{S_0}{S_0^{\text{max}}} \]

Normalized Degree of Linear Polarization:

\[ \rho_{\text{LL}} = \frac{S_1^2}{S_0} \]

Normalized Degree of Circular Polarization:

\[ \rho_{\text{CC}} = \frac{S_2^2}{S_0} \]

Normalized Circular Polarization Ratio:

\[ \rho_{\text{CR}} = \frac{|S_1|^2}{S_0} \]

Relative Phase:

\[ \phi = \angle (S_1, S_0) \]

Stokes' Child Parameters

Degree of Polarization:

\[ m = \sqrt{S_1^2 + S_2^2 + S_3^2} / S_0 \]

Degree of Linear Polarization:

\[ m_{\text{LL}} = (S_1^2 + S_2^2) / S_0 \]

Degree of Circular Polarization:

\[ m_{\text{CC}} = S_2^2 / S_0 \]

Circular Polarization Ratio:

\[ m_{\text{CR}} = |S_1|^2 / S_0 \]

Linear Polarization Ratio:

\[ m_{\text{LR}} = (S_1 - S_2) (S_1 + S_2) / S_0^2 \]

Relative Phase:

\[ \phi = \angle (S_1, S_0) \]

Stokes Vector:

\[ \mathbf{S} = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} \]

Stokes' Vector

\[ \mathbf{S} = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} \]

Polarization Synthesis

The antennas and Stokes vectors can be generated as:

\[ \mathbf{S} = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} \cos(2\chi) \cos(2\phi) \\ \sin(2\chi) \cos(2\phi) \\ \sin(2\phi) \sin(2\chi) \\ \cos(2\phi) \sin(2\chi) \end{bmatrix} \]

Polarization Signatures (Theoretical models)

CO-POL

CROSS-POL

SPHERE

ROUGH SURFACE

DIHEDRAL

21-12-2016
A well-known example of polarimetric observations were made by AIRSAR of San Francisco's Golden Gate region. At the time, AIRSAR collected the full polarization matrix of the region.

Once collected, it is possible to look at the power returned under different polarization combinations.

\[ E_h E_h^* = E_h \]

- **Orthogonal Tx Pols**
  - No symmetry
  - 4x4 scattering matrix
  - 3x3 scattering matrix
  - 3x3 pseudo scattering matrix
  - 2x2 covariance matrix

- **One Tx Pol., Coherent Dual Rx**
  - NO symmetry assumption
  - 2 magnitudes & co-pol phase

- **Two Tx Pols**
  - NO symmetry assumption
  - 2 magnitudes

- **Two Rx Pols**
  - NO assumptions
  - 2 magnitudes

**Image Speckle Filters**

- **Multi-look**: (aisims) correlation with \( c = \text{Res} \times 2 \)

- **Mean Filter**: Box Car
- **Sigma Filter**: based on std dev. (sigma) statistics
- **Stiff**: Minimum Mean Square Error filter
- **Lee Filter**: Local statistics method
- **Frost Filter**: considers damping factor
- **Refined Lee filter**: Better edge preservation
- **Gamma Map Filter**: 
- **IDAN Filter**: Intensity Driven Adaptive Neighborhood filter
- **SOFM Filter**: Self Organizing Feature Map based Filter

**Image Speckle Filters**

**Columns (range)**

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

**Range Resolution = \( c/\beta = 1.2 \times 10^6 / 15.5 \times 10^6 = 9.677 \text{ meters} \)**

**Ground Range = \( C / [\beta x \sin(23^\circ)] = 24.76 \text{ m} \approx 25 \text{ m} \)**

**Azimuth Resolution = \( L_a / 2 = 10\text{ m} / 2 = 5\text{ m} \)**

**Appropriate Multi-look Factor = \( \text{Gr} / \text{Ra} / \text{Az Resolution} = 5 \)**
Effect of Polarimetric Filters on Classification

ALOS PALSAR Data of Mumbai Region

ALOS RGB | Without Filter | BoxCar | Refined Lee

The measured scattering matrix is expressed as a combination of the scattering responses of simpler objects

\[ s = \sum_{i=1}^{N} \beta_i t_i \]

Component (Freeman-Durden)
Eigen vector based (Cand2) (Strobl)
Entropy-Alpha (Cloude-Pottier)

Yamaguchi RGB | Without Supervised classification

Mixed forest
Teak dominated forest
Scattered trees / degraded forest
Young plantation (teak / acacia)
Plantation crops / paddy
Bare field / fallow
Water body
Built-up area

Polarimetric Decomposition

Wishart Supervised classification
**Dichotomy of the Kennaugh Matrix K:**

Phenomenological Huynen Decomposition

Barnes-Holm Decomposition

Yang Decomposition

Eigenvector-Based Decomposition:

Cloude Decomposition

Cloude and Pottier Decomposition (Entropy - alpha Decomposition)

Holm Decomposition

van Zyl Decomposition (NNED Decomposition)

**Model-Based Decomposition:**

Freeman-Durden Three-Component Decomposition

Moriyama Decomposition

Yamaguchi Decomposition (4-component Decomposition)

Freeman Two-Component Decomposition

**Coherent Decomposition:**

Pauli Decomposition

Krogager Decomposition (SDH Decomposition)

Cameron Decomposition

Polar Decomposition

---

**Pauli Decomposition**

Complex 2 x 2 scattering matrix representing the Electric fields of transmitted and received wave:

\[
\begin{pmatrix}
S_{hh} & S_{hv} \\
S_{vh} & S_{vv}
\end{pmatrix}
\]

Pauli matrices and their interpretation in the \((E_h, E_v)\) polarization basis

**Limitations:**

A double-bounce reflector shows up in two different components, one representing an unrotated dipole, another representing a 45° tilted dipole, which renders the interpretation somehow ambiguous.

---

**Linear Lexicographic**

**Pauli Decomposition**

Example:

\[
S_{hh}, S_{hv}, S_{vv}
\]

ALOS-PALSAR Full Pol Data over Guwahati Region
Krogaer Decomposition

Spherical Polar Decomposition

Based on the observation that any given symmetric scattering matrix can be represented in terms of the elementary symmetric matrices for a sphere, a dihedral (dipole), and a helix.

\[
[S] = e^{i \theta} [K_1 S_{\text{ball}} + K_2 S_{\text{dihedral}} + K_3 S_{\text{helix}}]
\]

In terms of the elements of the scattering matrix in a circular polarization basis, the parameters of this decomposition are given as follows:

- k = -j\omega a \sin \theta
- k = j\omega a \cos \theta
- \omega = -i (\omega_0 + \omega_a)
- \theta = \frac{1}{2} (\omega_0 - \omega_a)
- \phi = \frac{1}{2} (\omega_0 + \omega_a)
- \psi = \frac{1}{2} (\omega_0 - \omega_a)

The advantage of this orientation invariant representation is that a pure one-helical component shows up in just one component.

Cameron Decomposition

Inspired by the work of Wegner (1965), Cameron introduced an approach based on the concept of symmetry.

\[
[S] = S_{\text{ball}} + \phi S_{\text{dihedral}} + \phi S_{\text{helix}}
\]

In terms of the elements of the scattering matrix in a circular polarization basis, the parameters of this decomposition are given as follows:

- k = -j\omega a \sin \theta
- k = j\omega a \cos \theta
- \omega = -i (\omega_0 + \omega_a)
- \theta = \frac{1}{2} (\omega_0 - \omega_a)
- \phi = \frac{1}{2} (\omega_0 + \omega_a)
- \psi = \frac{1}{2} (\omega_0 - \omega_a)

IN-COHERENT DECOMPOSITIONS

Target Symmetry in SAR Polarimetry

Reflection Symmetry

Rotation Symmetry

Azimuthal Symmetry
The Covariance matrix can be expressed in terms of the sum of the Volume, Double bounce and Surface scattering components:

\[ \text{Total Power: } P = P_{\text{surf}} + P_{\text{double-bounce}} + P_{\text{surface}} \]

Where:

\[ P_{\text{surf}} = f_{\alpha}(1 + \beta) \]
\[ P_{\text{double-bounce}} = f_{\beta}(1 + \alpha) \]
\[ P_{\text{surface}} = \text{f}_{\text{surf}}(1 + \alpha + \beta) \]
NO scattering \(\alpha\) on NO

Odd (surface) scattering contribution:

\[ f_{\text{Odd (surface)}} = \frac{a}{g_{1} + g_{2}} \]

Non-

Even (double) scattering contribution:

\[ f_{\text{Even (double)}} = \frac{a}{g_{3} + g_{4}} \]

Estimation of cross scattering

\[ S_{\text{cross}} = f_{\text{cross}} \]

Surface, Volume, and Double-Bounce

More suitable for urban classification

More suitable for forest classification

Yamaguchi Four-Component Decomposition

The three-component scattering power model proposed by Freeman and Urban can be successfully applied to describe SAR observations from theMoriyama Decomposition. However, it can be possible to find areas in an SAR image for which the reflection symmetry condition does not hold.

Based on the three-component scattering model approach, Yamaguchi et al. proposed, in 2005, a four-component scattering model by introducing an additional term corresponding to reflected components.

\[ \begin{cases} \langle S_{\text{hh}} S_{\text{hh}} \rangle = 0 \\ \langle S_{\text{vv}} S_{\text{vv}} \rangle = 0 \end{cases} \]

He introduced a fourth component equivalent to the reflection scattering power corresponding to this new four-component case.

The fifth component appears in heterogeneous areas (complicated shape targets or massive structures) whereas disappears for almost natural distributed scattering.

\[ S_{\text{PP}} = S_{\text{HH}} + S_{\text{VV}} \]

\[ S_{\text{III}} = S_{\text{HH}} + S_{\text{VV}} \]

\[ S_{\text{II}} = S_{\text{HH}} + S_{\text{VV}} \]

\[ S_{\text{IV}} = S_{\text{HH}} + S_{\text{VV}} \]
Polarimetric Mueller and Kennaugh Matrices

For pure target case, there exists a one-to-one correspondence between the Kennaugh matrix and the coherency \( T_v \) matrix, given by:

\[
\begin{pmatrix}
A & B & C \\
B & D & E \\
C & E & F
\end{pmatrix} = \begin{pmatrix}
2A & C + D & H \\
C + D & B & F + \gamma B \\
H & F + \gamma B & A - C - D
\end{pmatrix}
\]

Where:

\[
A = \frac{1}{2}(S + \nu \nu^* - \nu h h^*) \\
B = \frac{1}{2}(S + \nu \nu^* + \nu h h^*) \\
C = \frac{1}{2}(S - \nu \nu^* - \nu h h^*) \\
D = \frac{1}{2}(S - \nu \nu^* + \nu h h^*) \\
E = \frac{1}{2}(S^* - \nu \nu^* - \nu h h^*) \\
F = \frac{1}{2}(S^* - \nu \nu^* + \nu h h^*)
\]

The van Zyl Decomposition (NNED Decomposition)

The van Zyl decomposition was first introduced in a general description of the 3x3 coherency \( C \) matrix for naturally elliptically polarized natural echoes in the monostatic case:

\[
C = \begin{pmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{pmatrix}
\]

The van Zyl decomposition shows that the first two eigenvalues represent equivalent scattering matrices that can be interpreted in terms of odd and even numbers of reflections.
Segmentation of H, A, \( \alpha \) Planes

Polarimetric Decompositions

Segmentation of H / A / \( \alpha \) Planes

Polarimetric Classifications

ADVANCED CONCEPTS IN SAR POLARIMETRY

Hybrid Polarimetry
Transmitting in Circular polarization reduces complexity of SAR while retaining polarimetric information of the wave in the backscattered field (far field)

Formula:
\[ \Omega = \frac{K}{f^2} \int NH \cos \theta \sec \chi \, d\theta \] [rad]

Annotated Diagram:
- \( K \): Faraday Rotation
- \( f \): Radio propagation frequency (Hz)
- \( N \): Earth's magnetic field intensity (amp./m)
- \( H \): Earth's magnetic field magnitude (amp/m)
- \( \chi \): Angle between normal to the wave direction and Earth's magnetic field
- \( \theta \): Vertical angle of the ray

Table:
<table>
<thead>
<tr>
<th>Polarity</th>
<th>C-Band (6 cm)</th>
<th>L-Band (14 cm)</th>
<th>P-Band (68 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td>( 2.9^\circ )</td>
<td>( 40^\circ )</td>
<td>( 321^\circ )</td>
</tr>
</tbody>
</table>

Image of Prof. Keith Roney

Reference:
- RR. Freeman, John Hopkins University, USA
### Hybrid Polarimetry

<table>
<thead>
<tr>
<th>Mode</th>
<th>Transmit</th>
<th>Receive 1</th>
<th>Receive 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular</td>
<td>RC</td>
<td>RC</td>
<td>LC</td>
</tr>
<tr>
<td>Hybrid</td>
<td>LC</td>
<td>H</td>
<td>V</td>
</tr>
</tbody>
</table>

Target Vector: \( \vec{d} = \begin{pmatrix} \frac{k_H}{j} \\ \frac{k_V}{j} \end{pmatrix} \)

### Various Hybrid (Compact) polarimetric Modes

- \( HH - HV \)
- \( HV - VV \)
- \( HH - JHV \)
- \( HV - JVV \)
- \( HH - HV \)
- \( HV - VV \)

### Summary of L-Band Crop Classification using 1-band PolSAR data at different polarization combinations

<table>
<thead>
<tr>
<th>Feature Name</th>
<th>Full-Pol Complex Intensity</th>
<th>Intensity</th>
<th>Full-Pol Complex Intensity</th>
<th>Intensity</th>
<th>Full-Pol Complex Intensity</th>
<th>Intensity</th>
<th>Overall Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mangrove</td>
<td>95.63</td>
<td>88.87</td>
<td>88.38</td>
<td>95.84</td>
<td>94.60</td>
<td>91.02</td>
<td>91.06</td>
</tr>
<tr>
<td>Water</td>
<td>95.76</td>
<td>77.06</td>
<td>75.88</td>
<td>81.08</td>
<td>59.56</td>
<td>72.20</td>
<td>70.62</td>
</tr>
<tr>
<td>Agricultural Bare Field</td>
<td>85.79</td>
<td>76.26</td>
<td>76.38</td>
<td>81.91</td>
<td>68.97</td>
<td>80.33</td>
<td>80.33</td>
</tr>
<tr>
<td>Village Vegetation</td>
<td>100</td>
<td>99.75</td>
<td>100</td>
<td>100</td>
<td>98.18</td>
<td>99.09</td>
<td>98.92</td>
</tr>
<tr>
<td>Wetland</td>
<td>97.24</td>
<td>66.90</td>
<td>66.21</td>
<td>95.17</td>
<td>76.55</td>
<td>80.69</td>
<td>80.69</td>
</tr>
<tr>
<td>Overall Accuracy</td>
<td>95.11</td>
<td>81.55</td>
<td>81.55</td>
<td>70.95</td>
<td>70.95</td>
<td>70.95</td>
<td>89.16</td>
</tr>
</tbody>
</table>

### Classification accuracy (Wishart Supervised) test of ALOS PolSAR polarimetric data of Sundarvan using various polarimetric combinations

- Full-Pol Complex: 91.02
- Intensity: 91.06
- Overall Accuracy: 91.06

### Full vs Hybrid Polarimetry

- Classification accuracy (Wishart Supervised) test of ALOS PolSAR polarimetric data of Sundarvan using various polarimetric combinations

### Feature 

- Full-Pol Complex Intensity: 91.55
- Intensity: 91.06
- Overall Accuracy: 91.06

### Reference

The transmitted field from the Mini-RF radars is elliptically polarized, with a dominant linearly polarized component. The m-b method may work in most applications when the Tx field is perfectly circular, but not if the Tx field has a linearly polarized component. The sign of $\chi$ is an unambiguous indicator of even versus odd bounce backscatter, even if the reflected EM field is not perfectly circularly polarized.

Since (degree of circularity) can be calculated from Stokes parameter by:

$$\tan 2\chi = \frac{2R_{SV}}{S_0}$$

-45° ≤ $\chi$ ≤ +45°

### Scattering mechanism

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_0$</td>
<td>Stokes vector</td>
<td>$S_0 = \begin{pmatrix} S_0 \end{pmatrix}$</td>
</tr>
<tr>
<td>$S_1$</td>
<td>First Stokes component</td>
<td>$S_1 = \begin{pmatrix} S_1 \end{pmatrix}$</td>
</tr>
<tr>
<td>$S_2$</td>
<td>Second Stokes component</td>
<td>$S_2 = \begin{pmatrix} S_2 \end{pmatrix}$</td>
</tr>
<tr>
<td>$S_3$</td>
<td>Third Stokes component</td>
<td>$S_3 = \begin{pmatrix} S_3 \end{pmatrix}$</td>
</tr>
</tbody>
</table>

**Stokes vectors (RC-HYB)**

- The transmitted field from the Mini-RF radars is elliptically polarized, with a dominant linearly polarized component.
- The m-b method may work in most applications when the Tx field is perfectly circular, but not if the Tx field has a linearly polarized component.
- The sign of $\chi$ is an unambiguous indicator of even versus odd bounce backscatter, even if the reflected EM field is not perfectly circularly polarized.

### Decomposition of Hybrid Polarimetric SAR data

- **m-b (alpha) decomposition**
  - $S_0 = \begin{pmatrix} S_0 \end{pmatrix}$
  - $S_1 = \begin{pmatrix} S_1 \end{pmatrix}$
  - $S_2 = \begin{pmatrix} S_2 \end{pmatrix}$
  - $S_3 = \begin{pmatrix} S_3 \end{pmatrix}$

### Rayleigh scattering model

- **Degree of Polarization**: $P = \frac{S_2^2 + S_3^2}{S_0^2}$
- **Degree of Circularity**: $C = \frac{S_2}{S_0}$
- **Degree of Linear polarization**: $L = \frac{S_1}{S_0}$

### Rayleigh scattering parameters

- $S_0 = \begin{pmatrix} S_0 \end{pmatrix}$
- $S_1 = \begin{pmatrix} S_1 \end{pmatrix}$
- $S_2 = \begin{pmatrix} S_2 \end{pmatrix}$
- $S_3 = \begin{pmatrix} S_3 \end{pmatrix}$

### Microwave scattering mechanism

- **Stokes vectors**: $S_0, S_1, S_2, S_3$
- **Eigenvectors**: $\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3$
- **Eigenvalues**: $\lambda_1, \lambda_2, \lambda_3$

### Poincare sphere

- **Stokes Parameters**: $S_0, S_1, S_2, S_3$
- **Degree of Circularity**: $C = \frac{S_2}{S_0}$
- **Degree of Polarization**: $P = \frac{S_2^2 + S_3^2}{S_0^2}$

### Scatterers

- **Volume Scatterers**: $V$
- **Scatterers**: $S$
- **Depolarized Scatterers**: $D$

### Relative RH-RV Phase ($\Delta \phi$)

- **Basin Sarah (BSA)**
- **Relative RH**: $0.0, 0.25, 0.50, 0.75, 1.0$
- **Degree of Polarization**: $m$

### Image color scheme

- **Relative RH**: $0.0, 0.25, 0.50, 0.75, 1.0$
- **Degree of Polarization**: $m$
- **Volume Scatterers**
- **Scatterers**
- **Depolarized Scatterers**

### Image color scheme

- **Relative RH**: $0.0, 0.25, 0.50, 0.75, 1.0$
- **Degree of Polarization**: $m$
- **Volume Scatterers**
- **Scatterers**
- **Depolarized Scatterers**
Analysis of RISAT-1 Hybrid Pol (cFRS) Data

Phase Coherency: RISAT-1 Hybrid pol data

Table: Classification Accuracy

<table>
<thead>
<tr>
<th>Class</th>
<th>Linear Pol</th>
<th>Hybrid Pol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban</td>
<td>70.77%</td>
<td>70.68%</td>
</tr>
<tr>
<td>Water</td>
<td>95.19%</td>
<td>94.99%</td>
</tr>
<tr>
<td>Forest</td>
<td>73.50%</td>
<td>78.85%</td>
</tr>
<tr>
<td>Mangroves</td>
<td>80.09%</td>
<td>82.88%</td>
</tr>
<tr>
<td>Wetland</td>
<td>62.57%</td>
<td>73.11%</td>
</tr>
</tbody>
</table>

Accuracy (%)

21-12-2016
Analysis of RISAT-1 Hybrid Pol (cFRS) Data

Land cover classification: Comparison of RISAT Hybrid Pol Data with Radarsat-2 Pol Data

<table>
<thead>
<tr>
<th>Class</th>
<th>RISAT-1</th>
<th>Radarsat-2</th>
<th>Overall Acc. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>78.59</td>
<td>99.95</td>
<td>99.05</td>
</tr>
<tr>
<td>Mangroves</td>
<td>60.60</td>
<td>75.25</td>
<td>70.72</td>
</tr>
<tr>
<td>Urban</td>
<td>56.74</td>
<td>91.73</td>
<td>92.25</td>
</tr>
<tr>
<td>Forest</td>
<td>56.15</td>
<td>52.87</td>
<td>54.94</td>
</tr>
<tr>
<td>Wetland</td>
<td>60.22</td>
<td>97.09</td>
<td>98.26</td>
</tr>
</tbody>
</table>

Overall Acc. % 64.17 81.53 81.86 81.35 80.68 80.91

Comparison of Hybrid (RISAT-1) and Simulated Hybrid (Radarsat-2) Pol Data

Paul RGB
RADARSAT-2: Mar. 10, 2014

Raney RGB (m-chi)
RISAT-1: Mar. 9, 2014

Raney RGB (m-chi)
RADARSAT-2 Simulation

Comparison of Hybrid (RISAT-1) and Simulated Hybrid (Radarsat-2) Pol Data

Raney Compact RADARSAT-2 Decomposition

Histogram of CPR for training areas

Table: Classification accuracies for RISAT-1 Hybrid datasets of Mahanadi Flood Plains for various land cover features with Wishart and SVM classifiers.
APPLICATIONS OF RISAT-1 DATA FOR VEGETATION STUDIES

Identification paddy crop using SAR decomposition image

Sketch of the three major scattering terms contributing to the total backscattering from summer paddy field with dry/wet soil (left image) and standing water (right image)

Application of RISAT-1 Data for Crop Monitoring

Retrieval of Forest Biomass using RISAT-1 FRS Dual Polarization Backscatter Data

Multi-Linear Regression (MLR) Based Model

Field Measured biomass (t/Ha)

Estimated biomass (t/Ha)

Approach

Statistical analysis

MLR Model

Model Validation

Image Statistics (Backscatter in dB)

Study Area: Saraswati Plantation Area, Kaithal, Haryana

Veg. Type: Plantation (Eucalyptus, Acacia, Prosopis Juliflora)

Data Used: FRS-1 HH+HV and RH+RV

Field Measured biomass (t/Ha)

Estimated biomass (t/Ha)
Area: Saraswati Plantation area, Kaithal Dist. Haryana (Dominant vegetation species: Eucalyptus, Acacia, Prosopis Juliflora)

RISAT-1 CFRS Data: 03 Mar 2013 (Inc. Angle: 48.7 deg.)
Multi-Linear Regression Model:
Biomass = \( a + b \cdot \sigma^R_{HH} + c \cdot \sigma^R_{HV} \)

Effect of Leaf-on and Leaf-off on SAR Data

RISAT-1 MRS Data: Shimoga Forest (Karnataka)
HH/HV Backscatter ratio (dB)

\( R^2 = 0.59 \)
\( R^2 = 0.51 \)
\( R^2 = 0.80 \)

ALOS-2 PALSAR-2 (JAXA)

ALOS-2 carries a Phased Array type L-band SAR (PALSAR-2) with many advanced imaging parameters.

Brief Specifications of PALSAR-2:

- Frequency: L-band (Spatially Stepped, and FastScan modes)
- Polarization: Single/Dual/Polarized
- Instantaneous Field of View: 52 km
- Ground Resolution: 30 m (swath: 25 km ~ 350 km)
- The L-band SAR will facilitate various Geo-science Applications over the course of its five-year mission.

ALOS-2 launched on 23 May 2014.
RISAT-3 (L-band) is a follow-up mission for RISAT-1 (C-band) with many advanced imaging parameters.

**Brief Specifications of RISAT-3:**
- **Frequency:** 2025 GHz (Spotlight, Stripmap and S-CandA modes)
- **Polarization:** Dual Pol / Circular
- **Incidence Angle:** 15–45 degrees
- **Ground Resolutions:** 1 m – 250 m (width) 50 m – 200 m

RISAT-3 will carry out various science applications over the course of its five-year mission life.

RISAT-3 satellite is planned for launch in 2018-19.

**NASA/ISRO Dual Frequency SAR Mission (NISAR):**

NISAR will carry L-band (1.25 GHz) and S-band (2.25 GHz) SAR with a 12m reflector antenna to catch the returning radar signal.

The NISAR radar has a spatial resolution better than 10m for characteristic dual geometries, some equivalent data from L band. The radar employs a novel imaging technique called SweepSAR that allows wide swath (~240 km) imaging at high resolution and full polarimetry.

The dual SAR will facilitate comparison of vegetation, ecosystem structure and dynamics of the earth, the mission of the five-year mission life.

BioSAR satellite is expected to launch in 2020.

**Biomass SAR (earlier BioSAR):**

Biomass SAR will be operated in P-band and will have a 12m reflector antenna to catch the returning radar signal.

The spacecraft will carry a novel radar system that is able to sense the trunks and big branches of trees from above.

Scientists will use Biomass to calculate the amount of carbon stored in the world’s forests, and to monitor for any changes over the course of the five-year mission.

Bio-SAR satellite is expected to launch in 2020.