Executive Summary

1) Hybrid-Polarity: Transmit circular; Receive H and V (and their relative phase)

2) In the dual-polarized context, it is one form of “compact polarimetry”

3) Generalizes to Quad-pol systems (with advantages… :~)
Polarimetric Imaging Radar Hierarchy

**Radar**
- Orthogonal Tx pols, Coherent Dual Rx
- One Tx Pol, Coherent Dual Rx
- Two Tx pols
- Two Rx pols

**Processing**
- No assumptions
- Reciprocity & symmetry
- Symmetry assumptions
- No symmetry assumptions
- 2 magnitudes & co-pol
- 2 magnitudes
- 2 magnitudes

**Result**
- 4x4 scattering matrix
- 3x3 scattering matrix
- Pseudo 3x3 scattering matrix
- 2x2 covariance matrix
- 2 orthogonal Like-pol images & CPD
- 2 orthogonal Like-pol images
- Like- and Cross-pol images
- Real image

**Nomenclature**
- Full polarization
- Quadrature polarization
- Compact polarization
- Dual polarization
- Mono-polarization

*NASA*
Dual Hybrid-Polarity Architecture (CL)

Transmit CP (note the 90° hybrid)
Receive (coherently) linear (H & V)

**Primary data product:**
2x2 covariance (or coherency) matrix of the observed field, or (subsequently) the 4-element Stokes vector.
The Stokes Parameters

*Highlights re: the coherent dual-pol received data*

- The four Stokes parameters are sufficient to fully characterize the observed (partially polarized quasi-monochromatic backscattered) EM field.

- Data products are rotationally-invariant with respect to illuminated features *iff* the transmit polarization is circular.
The Hybrid Dual-Polarized Architecture

Transmit circular polarization. Then

✓ The Stokes parameter values are independent of the polarization basis of the dual receivers
✓ Therefore, a linear basis on receive enjoys equivalent information content as classical circular receive polarity
✓ Receiver noise ($N_o$ per channel) appears only in $S_1$

**CL Hybrid Polarity**

<table>
<thead>
<tr>
<th>$S_1$</th>
<th>$S_2$</th>
<th>$S_3$</th>
<th>$S_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$= &lt;</td>
<td>E_{RH}</td>
<td>^2 +</td>
<td>E_{RV}</td>
</tr>
</tbody>
</table>

**Circular/circular**

<table>
<thead>
<tr>
<th>$S_1$</th>
<th>$S_2$</th>
<th>$S_3$</th>
<th>$S_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$= &lt;</td>
<td>E_{RH}</td>
<td>^2 +</td>
<td>E_{RV}</td>
</tr>
</tbody>
</table>

*Note the order of the subscripts*
The $-3$ dB SNR Issue: Hybrid-Dual Pol

**Circular** $\Rightarrow$ Simultaneous \cancel{\textcolor{red}{\#}} \textit{Linear Polarizations}

Transmit:

$\text{e.g. Right-Circular Polarization} \Rightarrow E_H - jE_V$

Consequence:

$\Rightarrow$ \textit{Splits power: Only 1/2 on either “H” or “V”}$\textcolor{red}{\cancel{\Rightarrow 3 dB SNR loss}}$

“Urban Legend”:

$\Rightarrow \text{Hybrid-polarity} \Rightarrow \text{3 dB SNR loss}$

Fact: Circular pol data products preserve SNR
Theorem 1: Conservation of Dual-pol SNR

“SC”: RCP data product: \( \frac{1}{2} [S_1 - S_4] = \langle |E_{RR}|^2 \rangle + N_o \)

“OC”: LCP data product: \( \frac{1}{2} [S_1 + S_4] = \langle |E_{RL}|^2 \rangle + N_o \)

QED

<table>
<thead>
<tr>
<th>CL Hybrid Polarity</th>
<th>Circular/circular</th>
</tr>
</thead>
<tbody>
<tr>
<td>S_1 = ( \langle</td>
<td>E_{RH}</td>
</tr>
<tr>
<td>S_2 = ( \langle</td>
<td>E_{RH}</td>
</tr>
<tr>
<td>S_3 = 2 \text{ Re} \langle E_{RH}E_{RV}^* \rangle</td>
<td>S_3 = 2 \text{ Im} \langle E_{RR}E_{RL}^* \rangle</td>
</tr>
<tr>
<td>S_4 = -2 \text{ Im} \langle E_{RH}E_{RV}^* \rangle</td>
<td>S_4 = -\langle</td>
</tr>
</tbody>
</table>
Observations 1: Hybrid Dual-Pol

- Nominal SNR is preserved (no 3-dB loss) in CP data products with hybrid-polarity dual-pol architecture
- (Generalization: SNR preservation is true iff the output basis is selected to match the transmitted basis)
- Covariance element values of the EM field do not depend on polarization basis of the receivers
- Stokes parameter values (and information content) do depend on the polarization basis of the transmitted field
- Hybrid- (Compact-) dual polarity extends to ScanSAR, enabling wide-swath (pseudo-) polarimetry
Hybrid-Quad-Pol Architecture

Transmit RC and LC polarizations, interleaved, at 2x Nyquist PRF
Receive (coherently) linear (H & V) after each transmission

Raw Full-polarimetric Data:
Transmit RC => \((A_{Rh}, A_{Rv})\)
Transmit LC => \((A_{Lh}, A_{Lv})\)
On Choice of Polarization Basis

The information content of the (scattering matrix) data product from a fully-polarized (or a quad-pol) radar is invariant with respect to the polarization basis of either the transmitted or the received EM fields.
Theorem 2: Conservation of Quad-pol SNR (1/3)

**Transmit:** L and R circular polarizations, Nyquist multiplexed

\[ E_L = E_h + jE_v \]
\[ E_R = E_h - jE_v \]

**Receive:** H and V polarizations (coherently) after each transmission

\[ A_{Lh} = a_{hh} + ja_{vh} + n_1 \]
\[ A_{Rh} = a_{hh} - ja_{vh} + n_3 \]
\[ A_{Lv} = a_{hv} + ja_{vv} + n_2 \]
\[ A_{Rv} = a_{hv} - ja_{vv} + n_4 \]

*NOTE:* include additive receiver noises
Theorem 2: Conservation of Quad-Pol SNR (2/3)

Assumptions

- **Additive noises:**
  - Zero-mean complex Gaussian
  - Statistically independent of the signals
  - Statistically independent of each other
  - Equal variances ($\langle |n_k|^2 \rangle = N_o$ for all $k$)

- **Cross-polarized signal terms**
  - eg: $a_{hv} = a_{vh}$ (reciprocity)
  - eg: $\langle a_{hh} a_{hv}^* \rangle = 0$ (statistical independence)
Theorem 2: Conservation of Quad-Pol SNR (3/3)

Then:

“HH” component: \( \langle |a_{hh}|^2 \rangle + \frac{1}{2} N_o \)

“VV” component: \( \langle |a_{vv}|^2 \rangle + \frac{1}{2} N_o \)

“HV” cross-product component: \( \langle |a_{hv}|^2 \rangle + \frac{1}{4} N_o \)

\[QED\]
The factor of “½” on the HH and VV noise terms balances the fact that only half of the power transmitted in circular pol is allocated to H or V, hence SNR is conserved.

The additional factor of “½” on the cross-pol noise term is a consequence of $a_{hv} \sim a_{vh}$ reciprocity, in exactly the same manner as conventional HV quad-pol systems.
Observations 2: Hybrid Quad-Pol SAR

- Nominal SNR is preserved (no 3-dB loss) in HH and VV data products with hybrid-polarity Quad-pol architecture
- \((This \ result \ generalizes \ to \ arbitrary \ polarization \ bases)\)
- Stokes parameter values—hence the information content—for quad-pol data products do not/not depend on polarization basis of either the transmitter or the receiver
- Choice of polarization bases (Tx and Rx) for a quad-pol radar can be driven by hardware optimization concerns (cross-talk, calibration, ambiguity levels, etc) since the architecture has no first-order impact on science
Hybrid Quad-Polarity: Selected Advantages

- Balanced (mean) signal levels in both channels
- Simpler hardware (e.g., no need for adaptive signal level compensation)
- Range ambiguity levels significantly reduced
- Direct observation of receive channel-to-channel phase/amplitude/spectral imbalances
- Calibrate without a corner reflector: looking at nadir => “H” statistically identical to “V”
- Standard “quad-pol” algorithms apply
Outlook

1) Two Hybrid-pol lunar “Mini-RF” radars (on Chandrayaan-1 and LRO)

2) C-band active phased-array Earth-viewing SAR RISAT, to be launched by India (ISRO) in 2009, includes a hybrid-dual-polarity mode

3) India (ISRO) has concluded Phase A studies for an earth-viewing L-band SAR based on hybrid polarity

4) Canada is studying Hybrid-Polarity dual-pol as a mode on Radarsat-3 (“Constellation”)

5) NASA JPL’s current SAR promotion is DESDynI (Deformation, Ecosystem Structure, and Dynamics of Ice), hosting a lidar/SAR dual payload; the SAR quad-pol mode will be hybrid-polarity

6) ALOS-2 initial plans include hybrid-polarity modes
Conclusions

- A Compact Polarimetry mode — especially Hybrid-polarity (*transmit circular/receive coherent linears*) — deserves consideration for any new orbital SAR

- For any quad- (or fully-) polarized SAR mode, Hybrid-polarity deserves consideration as the preferred architecture