Study of Polarimetric Calibration for Circularly Polarized Synthetic Aperture Radar

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L Band CP-SAR onboard JX-1

X Band CP-SAR System for Aircraft
Principle of Circularly Polarized Synthetic Aperture Radar (CP-SAR)

Rice paddy observation

<table>
<thead>
<tr>
<th>Category</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency [GHz]</td>
<td>4.5 to 7.5</td>
</tr>
<tr>
<td>Polarization</td>
<td>CP and LP</td>
</tr>
<tr>
<td>Number of samples</td>
<td>801</td>
</tr>
<tr>
<td>Number of azimuth point</td>
<td>359</td>
</tr>
<tr>
<td>Off-nadir angle [deg]</td>
<td>70 and 50</td>
</tr>
</tbody>
</table>
Background

- Rice paddy observation
  - Off nadir angle: 70deg  6 rice paddy
Full polarimetric calibration for Circularly polarized Radar system

- Concept
  - Well developed conventional calibration technique in linear polarization (LP) basis is used for calibration of circular polarization (CP) radar system.

- Objective
  - We utilize the two conventional calibration technique and modified it for CP full polarimetric calibration. The performance of the two calibration techniques in CP basis are validated by experiment inside an anechoic chamber.
The LP polarimetric calibration techniques used for CP polarimetric calibration

- Wiesbeck et al. technique
- Gau et al. technique
Polarimetric calibration method

The typical relationship between measured and theoretical scattering matrix

\[
\begin{bmatrix}
S_{m}^{m} & S_{m}^{LR} \\
S_{m}^{RL} & S_{m}^{RR}
\end{bmatrix}
= \begin{bmatrix}
I_{LL} & I_{LR} \\
I_{RL} & I_{RR}
\end{bmatrix}
+ \begin{bmatrix}
R_{LL} & R_{LR} \\
R_{RL} & R_{RR}
\end{bmatrix}
\begin{bmatrix}
S_{LL} & S_{LR} \\
S_{RL} & S_{RR}
\end{bmatrix}
+ \begin{bmatrix}
T_{LL} & T_{LR} \\
T_{RL} & T_{RR}
\end{bmatrix}
\]

Measured scattering matrix
Isolation matrix
Distortion matrix
Wiesbeck et al. technique modified for CP calibration technique

This technique solves the complete polarimetric error model, where every error coefficients of the distortion matrices can be solved by three calibration targets.

\[
\begin{bmatrix}
S_{LL}^m & S_{LR}^m \\
S_{RL}^m & S_{RR}^m
\end{bmatrix} = \begin{bmatrix}
I_{LL} & I_{LR} \\
I_{RL} & I_{RR}
\end{bmatrix} + \begin{bmatrix}
R_{LL} & R_{LR} \\
R_{RL} & R_{RR}
\end{bmatrix}\begin{bmatrix}
S_{LL} & S_{LR} \\
S_{RL} & S_{RR}
\end{bmatrix}\begin{bmatrix}
T_{LL} & T_{LR} \\
T_{RL} & T_{RR}
\end{bmatrix}
\]

Polarimetric calibration method

- Calibration targets
  - LP calibration
    - Cal 1: Sphere/circular disk
    - Cal 2: Dihedral
    - Cal 3: Dihedral 45°
  - CP calibration
    - Cal 1
    - Cal 2
    - Cal 3: Sphere/circular disk

- Calibration process

  Start

  Measure \([I]\) \rightarrow Measure \text{Cal} 1 \rightarrow Measure \text{Cal} 2 \rightarrow Measure \text{Cal} 3

  Calculate \([S]\) of Circular plate, Dihedral, and Dihedral 45°

  Derive error coefficients

  End
Gau et al. technique modified for CP calibration technique

This technique separate the channel effect and cross-talk coefficients in the model. Two calibration targets are utilized.

\[
\begin{bmatrix}
M_{LL}A_{LL} & M_{LL}A_{LR} \\
M_{LL}A_{RL} & M_{LL}A_{RR}
\end{bmatrix}
= 
\begin{bmatrix}
1 & \delta_y \\
\delta_x & 1
\end{bmatrix}
\begin{bmatrix}
S_{LL} & S_{LR} \\
S_{RL} & S_{RR}
\end{bmatrix}
\begin{bmatrix}
1 & \delta_x \\
\delta_y & 1
\end{bmatrix}
\]

Polarimetric calibration method

- Calibration targets
  - LP calibration
  - CP calibration

- Calibration process

**Start**

- Measure $[I]$ → Measure Cal1 → Measure Cal2
- Calculate $[S]$ of Circular plate, Dihedral
- Derive $\delta_x$, $\delta_y$ and $A_{xy}$

**End**
Polarimetric calibration method

- **Modified parts**
  - Calculating theoretical scattering matrix in CP-basis
    - Use of basis transformation matrix.

\[
\begin{bmatrix}
S_{LL} & S_{LR} \\
S_{RL} & S_{RR}
\end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix} \begin{bmatrix}
S_{HH} & S_{HV} \\
S_{VV} & S_{VV}
\end{bmatrix} \begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix}
\]

- Calibration targets
  - Combination of the calibration targets are different.
Calibration experiment and results

- **Experimental setup**
  - Frequency: 4.5~7.5 GHz
  - Number of samples for each frequency: 801
Calibration experiment and results

- **Calibration targets**

  - Circular plate (Single scattering)
    
    \[
    \begin{bmatrix}
    S_{LL} & S_{LR} \\
    S_{RL} & S_{RR}
    \end{bmatrix} =
    \begin{bmatrix}
    0 & j \\
    j & 0
    \end{bmatrix}
    \]

  - Dihedral (Double scattering)
    
    \[
    \begin{bmatrix}
    S_{LL} & S_{LR} \\
    S_{RL} & S_{RR}
    \end{bmatrix} =
    \begin{bmatrix}
    1 & 0 \\
    0 & -1
    \end{bmatrix}
    \]

  - Dihedral (45°) (Double scattering)
    
    \[
    \begin{bmatrix}
    S_{LL} & S_{LR} \\
    S_{RL} & S_{RR}
    \end{bmatrix} =
    \begin{bmatrix}
    e^{j90°} & 0 \\
    0 & -e^{-j90°}
    \end{bmatrix}
    \]

  CT1: Wiesbeck et al. technique modified for CP.

  CT2: Gau et al. technique modified for CP.

<table>
<thead>
<tr>
<th>Targets</th>
<th>CT 1</th>
<th>CT2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cal target 1</td>
<td>Vertical dihedral</td>
<td>Vertical dihedral</td>
</tr>
<tr>
<td>Cal target 2</td>
<td>Dihedral 45°</td>
<td>None</td>
</tr>
<tr>
<td>Cal target 3</td>
<td>Circular plate</td>
<td>Circular plate</td>
</tr>
</tbody>
</table>
Calibration experiment and results

- **Calibration reflectors**
  - Circular plate
    - 200mm (Diameter) (Large circular plate)
    - 150mm (Small circular plate)
  - Dihedral
    - 180x180x400mm (Large dihedral)
    - 150x150x200mm (Small dihedral)
Calibration experiment and results

<table>
<thead>
<tr>
<th>Measured target</th>
<th>Cal1, Cal2</th>
<th>Cal3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large circular plate</td>
<td>Small dihedral</td>
<td>Small circular plate</td>
</tr>
</tbody>
</table>

\[
\begin{bmatrix}
S_{LL} & S_{LR} \\
S_{RL} & S_{RR}
\end{bmatrix} = \begin{bmatrix}
0 & j \\
j & 0
\end{bmatrix}
\]

- **LR RCS (dBsm)**
  - Theoretical
  - CT1
  - CT2

- **Cross-polarization purity (dBsm)**
  - Measured
  - CT1
  - CT2

- **Amplitude ratio (RL-LR) [dB]**
  - Measured
  - CT1
  - CT2

- **Phase difference (RL-LR) [deg]**
  - Measured
  - CT1
  - CT2
## Calibration experiment and results

<table>
<thead>
<tr>
<th>Measured target</th>
<th>Cal1, Cal2</th>
<th>Cal3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small dihedral 45°</td>
<td>Large dihedral</td>
<td>Large circular plate</td>
</tr>
</tbody>
</table>

\[
\begin{bmatrix}
S_{LL} & S_{LR} \\
S_{RL} & S_{RR}
\end{bmatrix} = \begin{bmatrix} e^{j90^\circ} & 0 \\
0 & -e^{-j90^\circ}\end{bmatrix}
\]

### Graphs

- **LL RCS [dBsm]**
  - Theoretical
  - CT1
  - CT2
  - Frequency [GHz]: 4.5, 5, 5.5, 6, 6.5, 7, 7.5
  - RCS values range from 2 to 10 dBsm

- **Cross-polarization purity [dBsm]**
  - Measured
  - CT1
  - CT2
  - Frequency [GHz]: 4.5, 5, 5.5, 6, 6.5, 7, 7.5
  - Purity values range from -10 to -35 dBsm

- **Amplitude ratio (RR-LL) [dB]**
  - Measured
  - CT1
  - CT2
  - Frequency [GHz]: 4.5, 5, 5.5, 6, 6.5, 7, 7.5
  - Ratio values range from -0.8 to 0.4 dB

- **Phase difference (RR-LL) [deg]**
  - Measured
  - CT1
  - CT2
  - Frequency [GHz]: 4.5, 5, 5.5, 6, 6.5, 7, 7.5
  - Phase values range from 10 to 0°
Conclusion and Future work

**Conclusion**

- For basic study of CP GB-SAR system, we assessed the performance of the CP full polarimetric calibration techniques.
- Two calibration techniques are validated by experiment.

**Future work**

- The CP calibration technique for UAV, aircraft, and satellite will be investigated for next laboratory’s experiment.
Study of Polarimetric Calibration for Circularly Polarized Synthetic Aperture Radar

Thank you for your attention
Benefit of CP-SAR

- Circular polarizations (CP) performs better than the HH polarization at lower incidence angles [1-2].
- CP exhibits multiple benefits over linear polarization including CP avoids polarization losses due to misalignment
- CP is no need to keep the transmitting and receiving antenna in the same alignment; It has the ability to decrease interference between direct and reflected signal due to multipath propagation
- The CP has the advantage of compactness and low power requirement, since the transmission of CP microwave is not affected by the Faraday rotation effect in the ionosphere [3] etc

References
Specification CB-SAR:

Altitude ($h$): < 4,000 m
Frequency operation ($f$): 5.3 GHz
Single polarization: LP / CP
Pulse length ($t$): 11 - 17 ms
Pulse bandwidth ($B$): 326 - 447 MHz
Off nadir angle ($g_m$): 30 – 50 degrees
Platform (UAV) speed ($v$): 27.78 m/s
Signal to Noise ratio (SNR): 20 dB
Antenna length ($l$): 0.75 m
Antenna width ($w$): 0.2 m
Antenna efficiency: 80%

Noise temperature ($T$): 500 K
Noise Figure ($F$): 3 dB
Pulse repetition frequency (PRF): 1000 Hz
Swath width ($W_g$): < 600 m
Best azimuth resolution: 0.67 m
Best range ground resolution: 0.67 m
Duty cycle ($D_c$): 1.1% - 1.6%
Peak transmit power ($P_t$): < 400 Watts
Backscattering coefficient ($s^\circ$): -30 dB
TX Attenuator 0 dB to -20 dB
   (1 dB stepped setting by computer)
RX Attenuator -20 dB (fixed switch)

C Band SAR
(Center frequency: 5.6 GHz,
BW: 400 MHz) for disaster and
plantation monitoring
X Band SAR : Specification

<table>
<thead>
<tr>
<th>Items</th>
<th>Spec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center Frequency</td>
<td>9.4GHz</td>
</tr>
<tr>
<td>Frequency Bandwidth</td>
<td>800MHz</td>
</tr>
<tr>
<td>Transmit Power</td>
<td>1500W peak</td>
</tr>
<tr>
<td>Slant Range Resolution</td>
<td>1m</td>
</tr>
<tr>
<td>Azimuth Resolution</td>
<td>5m</td>
</tr>
<tr>
<td>Flight Altitude</td>
<td>~ 5,000m</td>
</tr>
</tbody>
</table>

X Band Antenna

CP-SAR Antenna : Tilted 30 degrees for downward

X Band CP-SAR System

Instruments

19inch size
### Specification of Microsatellite SAR

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Altitude</strong></td>
<td>Polar Orbit, 500～900 km</td>
</tr>
<tr>
<td><strong>Mission Devices</strong></td>
<td>Circular Polarized SAR (CP-SAR)</td>
</tr>
<tr>
<td><strong>Mission Devices</strong></td>
<td>Electron Density – Temperature Probe (EDTP)</td>
</tr>
<tr>
<td><strong>Mission Period</strong></td>
<td>1 - 3 Year</td>
</tr>
<tr>
<td><strong>Payload</strong></td>
<td>100kg – 150 kg</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>Average &lt; 600W</td>
</tr>
<tr>
<td><strong>Altitude Control</strong></td>
<td>3 axis, accuracy 0.1°</td>
</tr>
<tr>
<td><strong>Altitude Control</strong></td>
<td>CSS,IRU,STT,MAGS,GPSR,RWA,MTQ</td>
</tr>
<tr>
<td><strong>Data rate</strong></td>
<td>120Mbps</td>
</tr>
<tr>
<td><strong>Telecommunication</strong></td>
<td>S Band (TLM/CMD)</td>
</tr>
<tr>
<td><strong>Telecommunication</strong></td>
<td>X Band (Mission Data, 20 Mbps)</td>
</tr>
<tr>
<td><strong>Memory</strong></td>
<td>10 GBytes</td>
</tr>
<tr>
<td><strong>Size</strong></td>
<td>About 700 x 800 x 1850 mm (launch)</td>
</tr>
</tbody>
</table>

**Diagram:**
- Top +Z
- Forward +X
- Bottom -Z
CP-SAR Antenna: Tilted 30 degrees for downward
Polarimetric calibration method

The technique modified from Wiesbeck et al.

The error matrix is given by:

\[
\begin{bmatrix}
S^m_{RR} - I_{RR} \\
S^m_{LL} - I_{LL} \\
S^m_{RL} - I_{RL} \\
S^m_{LR} - I_{LR}
\end{bmatrix} =
\begin{bmatrix}
M_{RR} \\
M_{LL} \\
M_{RL} \\
M_{LR}
\end{bmatrix} =
\begin{bmatrix}
R_{RR}T_{RR} & R_{RL}T_{LR} & R_{RR}T_{LR} & R_{RL}T_{RR} \\
R_{LR}T_{RL} & R_{LL}T_{LL} & R_{LR}T_{LL} & R_{LL}T_{RL} \\
R_{RR}T_{RL} & R_{RL}T_{LL} & R_{RR}T_{LL} & R_{RL}T_{RL} \\
R_{LR}T_{RR} & R_{LL}T_{LR} & R_{LR}T_{LR} & R_{LL}T_{RR}
\end{bmatrix}
\begin{bmatrix}
S_{RR} \\
S_{LL} \\
S_{RL} \\
S_{LR}
\end{bmatrix} =
\begin{bmatrix}
\varepsilon_{11} & \varepsilon_{32} & \varepsilon_{33} & \varepsilon_{32}\varepsilon_{11} \\
\varepsilon_{31}\varepsilon_{41} & \varepsilon_{13} & \varepsilon_{22} & \varepsilon_{31}\varepsilon_{22} \\
\varepsilon_{11} & \varepsilon_{12} & \varepsilon_{22} & \varepsilon_{31} \\
\varepsilon_{31} & \varepsilon_{32} & \varepsilon_{33} & \varepsilon_{32}\varepsilon_{31}\varepsilon_{41} \\
\varepsilon_{31} & \varepsilon_{32} & \varepsilon_{33} & \varepsilon_{42}\varepsilon_{41} \\
\varepsilon_{41} & \varepsilon_{42} & \varepsilon_{44} & \varepsilon_{44}
\end{bmatrix}
\begin{bmatrix}
S_{RR} \\
S_{LL} \\
S_{RL} \\
S_{LR}
\end{bmatrix}
\]

- **Calibration requirement**
  - Three calibration targets should be utilized.
  - Linearly independent each other.
Polarimetric calibration method

The technique modified from Gau et al.

Channel effect: \( A_{xy} \)

Cross-talk coefficients: \( \delta_x, \delta_y \)

\[
\begin{bmatrix}
M_{LL}A_{LL} & M_{LL}A_{LR} \\
M_{LL}A_{RL} & M_{LL}A_{RR}
\end{bmatrix} = \begin{bmatrix}
1 & \delta_y \\
\delta_x & 1
\end{bmatrix} \begin{bmatrix}
S_{LL} & S_{LR} \\
S_{RL} & S_{RR}
\end{bmatrix} \begin{bmatrix}
1 & \delta_x \\
\delta_y & 1
\end{bmatrix}
\]

Calibration requirement

✓ Two calibration targets should be utilized
✓ Linearly independent