Calibration of Dual-Pol SAR data: a possible approach for Sentinel-1

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Outline

- Introduction: ESA Sentinel-1 C-band SAR
- Dual-pol radiometric calibration
  - Dual-pol distortion model
  - Response of passive calibration targets
  - Estimation of polarimetric distortion parameters
- Performance using Sentinel-1 system parameters
  - Performance results
  - Design and location of calibration targets
- Conclusions
## Sentinel-1 C-band SAR

### Key parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revisit time</td>
<td>12 days</td>
</tr>
<tr>
<td>Center frequency</td>
<td>5.405 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>&lt; 100 MHz</td>
</tr>
<tr>
<td>Polarization</td>
<td>HH/HV – VV/VH</td>
</tr>
<tr>
<td>Antenna azimuth size</td>
<td>12.4 m</td>
</tr>
<tr>
<td>Antenna elevation size</td>
<td>0.821 m</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>&gt; 5 m</td>
</tr>
<tr>
<td>Pulse width</td>
<td>&lt; 100 us</td>
</tr>
<tr>
<td>PRF</td>
<td>1000-3000 Hz</td>
</tr>
</tbody>
</table>
Sentinel-1 C-band SAR

Dual Polarimetric modes

S-1 dual-pol modes
Objective

To provide a polarimetric calibration procedure of dual-pol data

- when the SAR does not operate the full-pol mode
- using passive calibration targets

Dual-pol SAR Data → Estimation of polarimetric system distortions

1. Dual-pol distortion model
2. Response of some calibration targets
3. Performance according S-1 system parameters
Full-Pol Distortion Model

Transmitted and received field

\[
\begin{bmatrix}
E^r_h \\
E^r_v
\end{bmatrix} = Ae^{j\phi} \begin{bmatrix}
1 & \delta_2 \\
\delta_1 & f_1
\end{bmatrix} \begin{bmatrix}
\cos \Omega & \sin \Omega \\
-\sin \Omega & \cos \Omega
\end{bmatrix} \begin{bmatrix}
S_{HH} & S_{HV} \\
S_{VH} & S_{VV}
\end{bmatrix} \begin{bmatrix}
\cos \Omega & \sin \Omega \\
-\sin \Omega & \cos \Omega
\end{bmatrix} \begin{bmatrix}
1 & \delta_3 \\
\delta_4 & f_2
\end{bmatrix} \begin{bmatrix}
E^t_h \\
E^t_v
\end{bmatrix}
\]

- Distortion Rx
- Scattering matrix
- Faraday rotation
- Distortion Tx
Full-Pol Distortion Model

Distortion parameters

\[
\begin{bmatrix}
M_{HH} & M_{HV} \\
M_{VH} & M_{VV}
\end{bmatrix} = A e^{i \phi} \begin{bmatrix}
1 & \delta_2 \\
\delta_1 & f_1
\end{bmatrix} \begin{bmatrix}
\cos \Omega & \sin \Omega \\
-\sin \Omega & \cos \Omega
\end{bmatrix} \begin{bmatrix}
S_{HH} & S_{HV} \\
S_{VH} & S_{VV}
\end{bmatrix} \begin{bmatrix}
1 & \delta_3 \\
\delta_4 & f_2
\end{bmatrix} \begin{bmatrix}
N_{HH} & N_{HV} \\
N_{VH} & N_{VV}
\end{bmatrix}
\]

→ System distortion parameters
  → X-talk: \( \delta_1, \delta_2, \delta_3, \delta_4 \)
  → Channel imbalance: \( f_1, f_2 \) \hspace{1cm} \text{6 system distortion parameters}

→ Calibration matrices can be estimated using distributed target
  → Target reciprocity: \( S_{ij} = S_{ji} \)
  → Reflection symmetry: \( \langle S_{ii} S_{ij}^* \rangle = 0 \)
  → Known HH-VV phase difference (eg. surface scattering = 0)
Dual-Pol Distortion Model

→ Dual-pol model = (Full-pol model) x (1 0)ᵀ

→ Case of H-transmission

\[
\begin{pmatrix}
M_{HH} \\
M_{VH}
\end{pmatrix}
= A e^{j \phi} \begin{pmatrix}
1 & \delta_2 \\
\delta_1 & f
\end{pmatrix}
\begin{pmatrix}
\cos \Omega & \sin \Omega \\
\sin \Omega & \cos \Omega
\end{pmatrix}
\begin{pmatrix}
S_{HH} & S_{HV} \\
S_{VH} & S_{VV}
\end{pmatrix}
\begin{pmatrix}
\cos \Omega & \sin \Omega \\
-\sin \Omega & \cos \Omega
\end{pmatrix}
\begin{pmatrix}
1 \\
\delta_3
\end{pmatrix}
\]

Cross-talk: \( \delta_1, \delta_2, \delta_3 \)
Channel imbalance: \( f \)

\{ 4 system distortion parameters \}

→ The receiving distortion matrix is the same as in full-pol mode (e.g. HH/HV)
Dual-Pol Distortion Model

Azimuthally distributed target

\[ M_{HH} = S_{HH} + (\delta_2 + \delta_3)S_{VH} + \delta_2\delta_3S_{VV} \]

\[ M_{VH} = \delta_1S_{HH} + (\delta_1\delta_3 + f)S_{VH} + f\delta_3S_{VV} \]
Dual-Pol Distortion Model

Azimuthally distributed target

→ Measured scattering elements (assuming reciprocity and zero FR)
\[ M_{HH} = S_{HH} + (\delta_2 + \delta_3)S_{VH} + \delta_2 \delta_3 S_{VV} \]
\[ M_{VH} = \delta_1 S_{HH} + (\delta_1 \delta_3 + f)S_{VH} + f \delta_3 S_{VV} \]

→ Observed covariance elements (assuming azimuthal symmetry)
\[ O_{11} \equiv |S_{HH}|^2 \]
\[ O_{12} \equiv (\delta_1^* + f^* \delta_3^*)|S_{HH}|^2 + (f^* \delta_2 + f^* \delta_3 - 2f^* \delta_3^*)|S_{VH}|^2 \]
\[ O_{22} \equiv |f^2||S_{VV}|^2 \]

\[ |f^2|\delta_3^* O_{11} + f(\delta_1^* O_{11} - O_{12}) + (\delta_2 + \delta_3 - 2\delta_3^*)O_{22} = 0 \]

We need 3 additional equations
Trihedral

→ Ideal response

\[
[S_t] = A_t(\theta, \phi)e^{j\phi_t(\theta, \phi)} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}
\]

→ Measured response in the dual-pol mode

\[
\delta_2, \delta_3 << 1
\]

\[
M_{HH}^t = A_{cf}A_t e^{j\phi_t} (1 + \delta_2 \delta_3) \approx A_{cf}A_t e^{j\phi_t}
\]

\[
M_{VH}^t = A_{cf}A_t e^{j\phi_t} (\delta_1 + f\delta_3)
\]

Absolute calibration factor

\[
A_{cf} = \frac{M_{VH}^t}{A_t e^{j\phi_t}}
\]

\[
\tilde{M}_{VH}^t = \delta_1 + f\delta_3
\]
Oriented Dihedral

→ Ideal response

\[
[S_d] = A_d(\theta, \phi) e^{j\phi_d(\theta, \phi)} \begin{pmatrix} \cos 2\psi & \sin 2\psi \\ \sin 2\psi & -\cos 2\psi \end{pmatrix}
\]

→ Dihedral oriented at 45 deg

\[
[S_d]_{\psi=\pi/4} = A_d e^{j\phi_d} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}
\]

→ Measured response using the dual-pol model

\[
\tilde{M}_{HH}^d = \delta_2 + \delta_3 \\
\tilde{M}_{VH}^d = \delta_1 \delta_3 + f \cong f
\]
Estimation of distortion parameters

First approach

→ Distributed target + trihedral + 45-dihedral

→ Combining the four equations the solution is unique

1. Distributed target + trihedral + 45-dihedral
2. Combining the four equations the solution is unique
3. Dual-pol distortion parameters
4. Estimation of distortion parameters from dual-pol data

→ Dual-pol distortion parameters

\[ f = \tilde{M}_{VH}^d \]
\[ \delta_1 = \tilde{M}_{VH}^t - \tilde{M}_{VH}^d \frac{\tilde{M}_{VH}^d \tilde{M}_{VH}^t O_{11}^* + \tilde{M}_{HH}^d O_{22}^* - O_{12}^*}{2 O_{22}^*} \]
\[ \delta_2 = \tilde{M}_{HH}^d \frac{\tilde{M}_{VH}^d \tilde{M}_{VH}^t O_{11}^* + \tilde{M}_{HH}^d O_{22}^* - O_{12}^*}{2 O_{22}^*} \]
\[ \delta_3 = \frac{\tilde{M}_{VH}^d \tilde{M}_{VH}^t O_{11}^* + \tilde{M}_{HH}^d O_{22}^* - O_{12}^*}{2 O_{22}^*} \]
Gridded Trihedral

Second approach

- Classical trihedral with gridded base wires or thin plates (Ainsworth, 2006)
- The polarization parallel to the grid is reflected
- The polarization perpendicular to the grid is absorbed
- Back plates have the same effect as in the classical trihedral
- Grid spacing $d$ is small compared to the wavelength
**Gridded Trihedral**

**Second approach**

→ General scattering matrix (Sheen, 1992)

\[
[S_{gt}] = \frac{A_{gt} e^{j \phi_{gt}}}{\sin^2(\phi) + \cos^2(\phi) \sin^2(\theta)} \begin{pmatrix}
\sin^2(\phi) & -\sin(\phi) \cos(\phi) \sin(\theta) \\
-\sin(\phi) \cos(\phi) \sin(\theta) & \cos^2(\phi) \sin^2(\theta)
\end{pmatrix}
\]

→ Ideal response (vertical grid, \( \phi = 0 \)):

\[
[S_{gt}]_1 = A_{gt} e^{j \phi_{gt}} \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}
\]

→ Ideal response (horizontal grid, \( \phi = \pi / 2 \)):

\[
[S_{gt}]_2 = A_{gt} e^{j \phi_{gt}} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}
\]
Estimation of distortion parameters

Second approach

→ Measured response in the dual-pol mode:

→ H-gridded trihedral:

\[
\tilde{M}_{HH1}^{gt} = \delta_2 \delta_3 \\
\tilde{M}_{VH1}^{gt} = \delta_3 f
\]

→ V-gridded trihedral:

\[
\tilde{M}_{VH2}^{gt} = \delta_1
\]

→ Equations from: 1 simple trihedral + 2 gridded trihedrals

\[
f = \sqrt{\frac{\tilde{M}_{VH1}^{gt}}{\tilde{M}_{HH1}^{gt}} (\tilde{M}_{VH1}^{t} - \tilde{M}_{VH2}^{gt})}
\]

\[
\delta_1 = \tilde{M}_{VH2}^{gt}
\]

\[
\delta_2 = \sqrt{\frac{\tilde{M}_{HH1}^{gt}}{\tilde{M}_{VH1}^{gt}} (\tilde{M}_{VH1}^{t} - \tilde{M}_{VH2}^{gt})}
\]

\[
\delta_3 = \frac{\tilde{M}_{VH1}^{gt}}{\sqrt{\frac{\tilde{M}_{HH1}^{gt}}{\tilde{M}_{VH1}^{gt}} (\tilde{M}_{VH1}^{t} - \tilde{M}_{VH2}^{gt})}}
\]
Dual-Pol Data Calibration

Dual-pol VS single- and quad-pol calibration

→ Single Polarization
  → Trihedral Corner Reflector

→ Quad Polarization
  → Trihedral Corner Reflector + Distributed target

→ Dual Polarization
  → Trihedral Corner Reflector + (Distributed target) + Additional targets

Oriented dihedral  Gridded trihedral

Performance of the targets as seen by S-1?
Performance Evaluation
Sentinel-1
Performance evaluation

Gridded trihedral and oriented dihedral

Two criteria:
1. Large beam width of the calibration target compared with S-1 azimuth beam width
2. Polarimetric stationarity of the target as imaged by different azimuth angles (including pointing stability)
Performance evaluation

Sentinel-1: antenna beamwidth

Antenna beam width

Azimuth: $\phi_a = \frac{\lambda}{L_\phi} \cong 0.23^\circ$

Elevation: $\theta_a = \frac{\lambda}{L_\theta} \cong 3.43^\circ$
Performance evaluation

Sentinel-1: antenna stability

→ Antenna pointing stability

- Yaw ($\Delta \phi_y$): ± 0.01 deg
- Pitch ($\Delta \theta_p$): ± 0.01 deg
- Roll ($\Delta \psi_r$): ± 0.01 deg
Performance evaluation
Beamwidth

→ Gridded trihedral RCS
  → RCS assumed equal to the flat trihedral (Ruck, 1970)
  \[
  \sigma_{gr}(\theta, \phi) \approx \frac{4\pi}{\lambda^2} \lambda^2 \left(v - \frac{2}{v}\right)^2, \quad v(\theta, \phi) = \cos \theta + (\sin \phi + \cos \phi) \sin \theta
  \]

→ Dihedral RCS (derived from Hayashi, 2006)
  \[
  \sigma_{di}(\theta, \phi) \approx \frac{4\pi}{\lambda^2} a^2 b^2 \sin^2 \left(\frac{\pi}{4} - \phi\right) \frac{\sin^2(u)}{u^2}, \quad u(\theta, \phi) = \frac{2\pi}{\lambda} l \cos \theta \sin \phi
  \]

→ Beam width
  → Elevation plane (θ): GT and DIH have large beam width
  → Azimuth plane (φ)?
Performance evaluation

Beam width on azimuth plane

→ First criterium for S-1:

\[ BW_{S-1} = \phi_a + \Delta \phi_y < BW_{trg} \]

→ Plot for \( \theta = 30^\circ \) and \( l = 10\lambda \)

Dihedral is difficult to point 😞
Performance evaluation

Polarimetric noise

→ Average polarimetric noise:
  → Coherent averaging of scattering vectors from different angular positions: \( k = \begin{pmatrix} S_{HH} \\ S_{HV} \\ S_{VH} \\ S_{VV} \end{pmatrix} \)
  → Compared with the requirement on the cross-talk level: \( \delta_{req} = -30 \text{ dB} \)

→ Second criterion:

\[
\delta < \delta_{req}
\]

Average on azimuth beam width + yaw stability and pitch stability
\[
\delta(\theta_{ref}) = 1 - k(\theta_{ref}, 0) \cdot \left( \frac{1}{N_{\theta}N_{\phi}} \sum_{i} \sum_{j} k(\theta_{i}, \phi_{j}) \right)^{*}
\]

Average on roll stability
\[
\delta = 1 - k(0) \cdot \left( \frac{1}{N_{\psi}} \sum_{i} k(\psi_{i}) \right)^{*}
\]
Performance evaluation

Polarimetric noise

Dihedral noise above the requirement 😞

Requirement -30 dB

Gridded trihedrals noise below the requirement 😊

S-1 angle of incident
## Estimation of distortion parameters

### Comparison of the two approaches

<table>
<thead>
<tr>
<th>Distributed target + Trihedral + Oriented dihedral</th>
<th>Trihedral + 2 gridded trihedral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trihedrals and dihedrals are simple to construct</td>
<td>Gridded trihedrals require accurate construction of the grid</td>
</tr>
<tr>
<td>Oriented dihedral has a narrow beam width and it is difficult to orient</td>
<td>Gridded trihedrals have large beam width</td>
</tr>
<tr>
<td>The dihedral has high polarimetric noise due to roll pointing error</td>
<td>The average polarimetric noise is below the cross-talk requirement</td>
</tr>
<tr>
<td>Trihedrals and dihedrals are slightly affected by rain</td>
<td>The microwave absorber layer can be affected by rain</td>
</tr>
<tr>
<td>Require the identification of azimuthally distributed targets in the SAR image</td>
<td>Do not use azimuthal symmetry assumption</td>
</tr>
</tbody>
</table>
Dual-Pol calibration
Possible approach for Sentinel-1 using passive targets

→ Design

Trihedral + 2 gridded trihedral

triangular edge > 50 cm
grid spacing < 1.5 cm

→ Location

near range
far range
Dual-Pol Data Calibration

- Polarimetric calibration matrix

\[
\begin{pmatrix}
S_{cal}^{HH} \\
S_{cal}^{VH}
\end{pmatrix} = \frac{1}{\delta_2 f - \delta_1} \begin{pmatrix}
-f & -\delta_2 \\
-\delta_1 & 1
\end{pmatrix}
\begin{pmatrix}
M_{HH} \\
M_{VH}
\end{pmatrix}
\]

- The transmitting x-talk $\delta_3$ is important for evaluating the reliability of dual-pol measurements

\[
S_{cal}^{HH} = S_{HH} + \delta_3 S_{HV}
\]
\[
S_{cal}^{VH} = S_{VH} + \delta_3 S_{VV}
\]

- Faraday rotation can be corrected as optional step from external source (e.g. TEC data)
Conclusions

→ Dual-pol distortion model
  - Contains 1 transmitting x-talk and 3 receiving distortion parameters

→ Estimation of distortion parameters from dual-pol data
  - 1 trihedral and 2 gridded trihedrals are required
  - Gridded trihedrals provide large beam width and polarimetric noise within the requirement

→ Calibration procedure
  - Performed for each beam and for each mode
  - Faraday rotation can be corrected as optional step