A robust symmetry-based approach to exploit TerraSAR-X dual-pol data for targets at sea observation

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Introduction - Motivation

Target at sea monitoring finds its utmost importance in the field of maritime security.

- Ship traffic control
- Piracy and border control
- Oil pollution
- Platforms monitoring
Available methodologies for target at sea monitoring include:
Targets observation at sea by Synthetic Aperture Radar (SAR) offers:

**PRO**
- High resolution
- Wide area coverage
- 24 hours – 7 days capabilities
- Almost independent on weather conditions
- Single- and Multi-polarization

**CONS**
- Targets identification
- Revisit time
- Data processing

Robust, imaging mode independent and multi-frequency algorithm!
Methodology – Symmetry property

An Object $T$ is defined symmetric

$$\begin{align*}
\{P, Q\} & \in T \\
\{P', Q\} & \in T' \\
\overline{PQ} & = \overline{P'Q'} \\
P & \equiv P' \\
Q & \equiv Q'
\end{align*}$$

given a set of transformation $X \in \{\text{rotation about some axis}, \text{mirror reflection in a plane}; T' = X(T)\}$

linear translation
Methodology – Symmetry property

Symmetry has been widely used in PolSAR application, i.e. Decomposition, Calibration

- Man-made metallic target
- Not symmetric
- C has 9 non-0 elements

VS

- Natural distributed target
- Symmetric
- C has 5 non-0 elements

\[ C = \begin{pmatrix}
    |S_{hh}|^2 & \sqrt{2} \langle S_{hh}S_{hv} \rangle & \langle S_{hh}S_{vv} \rangle \\
    \sqrt{2} \langle S_{hv}S_{hh} \rangle & |S_{hv}|^2 & \sqrt{2} \langle S_{hv}S_{vv} \rangle \\
    \langle S_{vv}S_{hh} \rangle & \sqrt{2} \langle S_{vv}S_{hv} \rangle & |S_{vv}|^2 
\end{pmatrix} \]

\[ r = |\langle S_{xx}S_{xy} \rangle| \quad x, y \in \{h, v\} \]
Methodology – Data set

Coherent Dual-Pol TS-X HH/HV $\Theta = 30.51$ Coherent Dual-Pol TS-X VV/VH $\Theta = 39.7$

Time: 2009-07-15 at 06:30 UTC
Wind: 5.1 m/s SW
Targets: 8; Ground truth: 7 Ships (AIS)

Time: 2011-08-30 at 14:15 UTC
Wind: 2.2 m/s SE
Targets: 50; Ground truth: 21 (10 AIS)
Results – Symmetry on HH/HV

Two case studies: almost same incidence angle but different oceanic processes.

[Left] Ship and internal waves. [Right] Ship and calm water.

Different performances between Co- and Cross-pol are expected!!
Results – Ievoli Shine

- $r$
  - Target = 0.58
  - Clutter = 0.008
  - TCR = 69.3

- $\sqrt{HH}$
  - Target = 1.06
  - Clutter = 0.21
  - TCR = 5.03

- $\sqrt{HV}$
  - Target = 0.38
  - Clutter = 0.04
  - TCR = 9.81
Results – Beluga Eternity

- **(r)**
  - Target=2.33
  - Clutter=0.007
  - TCR= 317

- **sqrt(HH)**
  - Target=4.30
  - Clutter=0.18
  - TCR= 23.6

- **sqrt(HV)**
  - Target=0.30
  - Clutter=0.04
  - TCR= 7.45

\[
(r) \quad \sqrt{HH} \quad \sqrt{HV}
\]
Results – Symmetry on VV/VH
Results – Yasa Bodrum

Target=1.64  
Clutter=0.004  
TCR= 367

Target=2.02  
Clutter=0.08  
TCR= 26.8

Target=0.59  
Clutter=0.05  
TCR= 10.05
Target-to-Clutter-Ratio summary for the data set analyzed

Only targets with valid AIS report have been considered (target size: 12m<length<332m)!
Results

Target-to-Clutter-Ratio summary for the data set analyzed

TS-X 2009-07-15 at 06:30 UTC $\Theta = 30.51$

TS-X 2011-08-30 at 14:15 UTC $\Theta = 39.7$

Charts for targets with measured TCR < 200
Results – Detection

[Left] $r$ image processed with 3x3 moving window.  
[Right] Logical true-false output.

Standard TS-X dual-pol data (10000 x 24000 pixels) processed in few minutes!
## Results – Validation

### TERRA SAR-X Dual-Polarimetric Data Set

<table>
<thead>
<tr>
<th>ID</th>
<th>Date &amp; time (UTC)</th>
<th>Location</th>
<th>Polarization</th>
<th>Inc.angle (°)</th>
<th>Wind speed (m/s)</th>
<th>Wind dir.</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMG-1</td>
<td>2009-07-11; 18:14</td>
<td>Gibraltar</td>
<td>HH-HV</td>
<td>34.73</td>
<td>2.7</td>
<td>SE</td>
</tr>
<tr>
<td>IMG-2</td>
<td>2011-08-30; 14:15</td>
<td>San Francisco</td>
<td>VV-VH</td>
<td>39.69</td>
<td>2.2</td>
<td>SE</td>
</tr>
<tr>
<td>IMG-3</td>
<td>2009-07-15; 06:29</td>
<td>Gibraltar</td>
<td>HH-HV</td>
<td>30.51</td>
<td>5.1</td>
<td>SW</td>
</tr>
<tr>
<td>IMG-4</td>
<td>2009-09-21; 18:06</td>
<td>Spain</td>
<td>VV-VH</td>
<td>20.00</td>
<td>5.5</td>
<td>SE</td>
</tr>
<tr>
<td>IMG-5</td>
<td>2012-03-29; 23:57</td>
<td>Gulf of Mexico</td>
<td>VV-VH</td>
<td>43.00</td>
<td>5.0</td>
<td>SE</td>
</tr>
<tr>
<td>IMG-6</td>
<td>2012-04-12; 16:49</td>
<td>Naples</td>
<td>HH-HV</td>
<td>28.16</td>
<td>3-5</td>
<td>SW</td>
</tr>
<tr>
<td>IMG-7</td>
<td>2011-10-06; 09:28</td>
<td>South Korea</td>
<td>VV-VH</td>
<td>39.68</td>
<td>10-12</td>
<td>NW</td>
</tr>
</tbody>
</table>

### Summary of the Results Obtained by Processing the SAR Data

<table>
<thead>
<tr>
<th>ID</th>
<th>Targets</th>
<th>Ground truth</th>
<th>Detected targets</th>
<th>False negatives</th>
<th>False positives</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMG-1</td>
<td>70</td>
<td>57</td>
<td>68</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>IMG-2</td>
<td>50</td>
<td>21</td>
<td>48</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>IMG-3</td>
<td>8</td>
<td>7</td>
<td>8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>IMG-4</td>
<td>7</td>
<td>5</td>
<td>5</td>
<td>2</td>
<td>0</td>
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<tr>
<td>IMG-5</td>
<td>14</td>
<td>7</td>
<td>12</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>IMG-6</td>
<td>13</td>
<td>0</td>
<td>12</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>IMG-7</td>
<td>29</td>
<td>4</td>
<td>22</td>
<td>7</td>
<td>0</td>
</tr>
</tbody>
</table>

Conclusions

• Ocean clutter has been proved to follow the polarimetric symmetry at X-band in both cross-polarization combination (HH/HV and VV/VH).

• $r$ is an effective and efficient measure of the departure from the reflection symmetry, acting as clutter suppression while enhancing targets at sea.

• $r$ outperforms single polarization TCR independently of radar geometry and oceanic process (wind, waves, etc.)

• Target detection method proposed is fast with an overall detection performance of 97% (validated with ground truth data).

• Multi-frequency approach for target at sea detection.
Thanks for your attention!