Using co-cross polarization coherence from TOPS SLC S-1 data for wind field retrieval

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Odd signature of co-cross coherence

Simulated by (Tsai et al. 2000) for SeaWind/QuickSCAT and first observed in C-band RS2 by Zhang et al. 2012

- Even symmetry for Co and cross-pol NRCS with respect to wind direction
- Odd signature can be used for ambiguity removal and wind vector retrieval

Can we observe the same feature with Sentinel-1 data?
- Some S1 particularities: Noise level, TOPS imaging, no polarimetric calibration...
- Dependency on sea state? Incidence angle?
Background on reflection symmetry

A definition from Lee & Pottier Book

Reflection symmetry: “Physically, this means that whenever there is a contribution from a point P, represented by the associated scattering Sp matrix, there will always be a corresponding contribution from its image at point Q represented by the associated scattering Sq matrix.”

“If a scatterer has reflection symmetry in a plane normal to the incidence plane then [...] the cross-polar scattering coefficient will be uncorrelated with the copolar terms.”

For a resolution Cell

Hypothesis:

The symmetry is mainly impacted by the wind (waves impact is neglected)

Reflection symmetry:
- Valid in the case of upwind/downwind condition
- Valid when no directional preference at very low winds
- Not valid with cross-wind condition
Massive processing of SLC IW data

A challenge for IT ...

Volume issue: considering each SLC product is about 7GB, downloading, storing and then processing hundreds of images may become an issue

Rely on cluster:
CCP parameter has been processed on a large amount of SLC IW S-1 (about 27 TB !)
- 616 from S-1b (102 in 2016, 514 in 2017)

672 with H- polarization and 3231 with V- polarization

CCP processing time on a single machine would have been more than 80 000 minutes -> 56 days

Here, only processed in few hours ...

Some processing parameters:
- CCP calculated with multilooking of about 10 000 (1 km resolution) (51 in az. and 196 in range direction, to ensure square pixels on ground projected)
- Each burst processing are projected onto a regular lon/lat grid (no interpolation - Nearest Neighbor algorithm is used to ensure no additional multilooking)
- Data collocated with ECMWF wind field 0.125° - 3h
Real and imaginary parts of Co-cross coherence **NOT** centered at 0 when reflection symmetry is met (low wind for every relative wind angle, and then for upwind/downwind)
Consider medium-high situation at 10m/s and upwind/downwind situation

- Strong dependence of wind direction on the CCP/CCC parameters
- Offset of around 0.02/0.03 for the real & imaginary parts at upwind / down situation

What are the causes of these offsets? Link to IW sub-swaths?
Several error sources for the co- and cross polarization correlation estimates

- **Coherence estimator (Touzi et 96)?**
  - From simulation, it is shown bias for L=10000 looks is extremely small and not the cause

- **Non-stationarity of signals (Jiang et al. 2014)?**
  - Within the 10000 looks (1 x 1 km), heterogeneity of signals may occur with respect to high-resolution metocean variabilities
  - Some samples could be polarimetrically correlated -> tested with samples generator, but not reliable that this phenomenon occur regularly and thus impact the global statistics!

- **Decorrelation due to the thermal noise (Bamler et al, 1998)?**
  - Antenna isolation between the vertical and horizontal polarization channel (Yueh et al 2002)

-> towards a methodology for dual-polarimetric calibration??
Polarimetric distortion and calibration

For dual-pol S1 antenna, measured elements depend on cross-talk, channel imbalance, and noise as:

\[
\begin{pmatrix}
M_{vh} \\
M_{vv}
\end{pmatrix} = A e^{i\phi} \begin{pmatrix}
1 & \delta_1 \\
\delta_2 & f
\end{pmatrix} \begin{pmatrix}
S_{hh} & S_{vh} \\
S_{hv} & S_{vv}
\end{pmatrix} \begin{pmatrix}
\delta_3 \\
1
\end{pmatrix} + \begin{pmatrix}
N_{vh} \\
N_{vv}
\end{pmatrix}
\]

Following reciprocity in this monostatic system (HV = VH)

\[
\begin{cases}
M_{vh} \approx S_{vh} + \delta_3 S_{hh} + \delta_1 S_{vv} + N_{vh} \\
M_{vv} \approx f S_{vv} + (\delta_3 f + \delta_2) S_{vh} + N_{vv}
\end{cases}
\]

Assuming no channel imbalance (\(f\)), co-pol channels significantly higher than cross-pol, and negligible terms with 2\(^{nd}\) order cross-talk, the 3 observables can be written as:

\[
O_1 \equiv \sigma_0^{vv} = \langle |M_{vv}|^2 \rangle \approx \langle |S_{vv}|^2 \rangle + \langle |N_{vv}|^2 \rangle
\]

\[
O_2 \equiv \sigma_0^{vh} = \langle |M_{vh}|^2 \rangle \approx \langle |S_{vh} + \delta_3 S_{hh} + \delta_1 S_{vv}|^2 \rangle + \langle |N_{vh}|^2 \rangle
\]

\[
O_3 \equiv \rho_{vvvh} = \frac{\langle M_{vv} M_{vh}^* \rangle}{\sqrt{\langle |M_{vv}|^2 \rangle \ast \langle |M_{vh}|^2 \rangle}} \approx \frac{\langle S_{vv} S_{vh}^* \rangle + \delta_3 \langle S_{vvh} \rangle + \delta_1 \langle |S_{vv}|^2 \rangle + (\delta_3 + \delta_2) \langle |S_{vh}|^2 \rangle}{\sqrt{\langle |M_{vv}|^2 \rangle \ast \langle |M_{vh}|^2 \rangle}}
\]
In the condition of reflection symmetry:

- for surface scattering with HH / VV phase difference near 0, leading to:
  with PR the Polarisation Ratio between sigma0VV et sigma0HH

- Above formulas can be reformulated as:

\[
\frac{O_3 \sqrt{O_1 \ast O_2}}{P R} \approx \delta^*_3 \left( O_1 - \langle |N_{vv}|^2 \rangle \right) \left( \frac{1}{PR^{0.5}} \right) + \delta^*_1 \left( O_1 - \langle |N_{vv}|^2 \rangle \right) + \\
(\delta_3 + \delta_2) \left( O_2 - \langle |N_{vh}|^2 \rangle \right)
\]

Equation solved using a least-square minimization scheme for a set of averaged \((O_1, O_2, O_3)\) for:

- different wind conditions: up to 14 m/s every 1 m/s
- different incidence angle conditions: from 30 to 45° every 0.5°
- at reflection symmetry conditions only: with +/- 4.5° around 0 and 180° for upwind / downwind conditions

3 complex crosstalk values are found:
- \(d_1\): -39.20 dB -158.20 deg
- \(d_2\): -19.87 dB -135.10 deg
- \(d_3\): -38.38 dB 48.78 deg
Co-cross coherence at up- and down-wind condition where reflection symmetry hold with various wind condition
Observed O3 values are in full line, and retrieved simulated O3 values with optimized cross-talk parameters are in dot-full line.

→ Values of d1 and d3 measured using corner reflector is similar:
  \(-37.4 \pm 4.7\)dB [“Sentinel-1 annual performance report 2016”]
→ Unique estimation of d2, which cannot be measured by trihedral corners reflector

➡️ Unique Polarimetric calibration method to be further investigated (subswath dependence...?)
Before any advanced calibration

Real and imaginary parts of Co-cross coherence **NOT** centered at 0 when reflection symmetry is met (low wind for every relative wind angle, and then for upwind/downwind)
Real and imaginary parts of Co-cross coherence **NOW** centered at 0 when reflection symmetry is met (low wind for every relative wind angle, and then for upwind/downwind)
Ava tropical storm from S1A

S1A_IW / VVH
@ 2018/10/19 01:45:145 (dB)

S1A_IW / VVH
@ 2018/10/19 01:45:145 (dB)
From SCIHUB S1A with polarimetric calibration

Real part VVVH

Imag part VVVH
Azimuthal variation of Co-cross coherence (amplitude and phase) within a single burst

First idea was to test the impact of using NESZ information from IPF 2.9 - not solved !!!!
On its use for wind field retrieval?

- Can this information be used for to further constrain the wind estimation?
  1- Estimate quadrant for wind direction
      • Interest to help remove ambiguity on wind streaks-based wind direction
  2- Further constrain the Bayesian wind inversion using a Polarimetric GMF
      • Less (no?) dependency to ancillary model
      → At the moment, impossible, due to the burst jumps... Further work needed on correcting these effects.

- A good calibrated Doppler Centroïd does that already... BUT

  - The Polarimetric signal observed is related to the scatterers different locations in VV or VH:
      → Waves spectra in co-, cross-pol seem to explain this behavior, showing phase difference of the scatterers along the wave profiles.
      → Geometry effect mostly affected by wind
  - The Doppler signal is related to the relative surface speed of the scatterers, due to:
      • 1st: wind, 2nd: current
      → Can the PGMF bring complementary/independent view to more precisely decipher surface wind from surface current effects?
A unique new calibration method has been prototyped based on:

- Massive collocation process between SLC IW and ECMWF (about 27TB SLC processed)
- a priori null co-cross coherence only when reflection symmetry applied (upwind/downwind)
  → Unique estimation of 3 cross-talk parameters based on wide range of observations conditions (incidence angle, wind speed)
  → Calibrated co-cross coherence (amplitude, phase, real, imaginary parts) now in agreement with previous study (e.g. RS2)

- Strong signal inducing jumps between each bursts not corrected making polarimetric information unusable at the moment
  - Can be corrected (e.g. burst-to-burst continuity)
  - But where does it come from?

- Geophysical explanation for this polarimetric signal? phase difference of the scatterers along the wave profiles.

- Perspectives:
  - Better constrain the wind estimation
  - Bring additional information, especially relevant in presence of current
  - Better identify regions affected by heavy rain (especially in extreme wind conditions)
Questions?
SEOM Wind Algo

Legend
New
Existing

Cost Function J1
First Guess U, \Phi

VV
Pre-processing

VV NESZ (ESA/EXP)

VV L1

Doppler VV

\phi VV

Flag VV

NRCS VV

PGMF

? U, \Phi

Cost Function J2

VH Pre-processing

VH NESZ (ESA/EXP)

VH L1

Doppler VH

\phi VH

Flag VH

NRCS VH
This activity has been funded by ESA partly from SEOM S1 Ocean studies project and from S-1 Mission Performance Center (MPC)
Coherence estimator

Maximum likelihood estimator (MLE) for the coherence:

\[
\hat{\rho}_{vvh} \approx \frac{\sum_{j=1}^{L} S_{v}^{j} S_{vh}^{j*}}{\sqrt{\sum_{j=1}^{L} |S_{v}^{j}|^2 |S_{vh}^{j}|^2}}
\]

- Bias can be estimated for low number of looks (dependent on generalized hypergeometric function)

\[
E[|\hat{\rho}_{vvh}|] = \frac{\Gamma(L)\Gamma(1.5)}{\Gamma(L + 0.5)} \left(1 - |\hat{\rho}_{vvh}|^2\right)^L 
\times _1F_2\left(1.5, L; L + 0.5, 1; |\hat{\rho}_{vvh}|^2\right)
\]

- In our case, very high number of looks required to achieve unbiased coherence estimates, products generated at 1km resolution -> for IW 195 x 51 looks, i.e. about 10000 looks
- A generator of correlated samples has been implemented

Dash-line: theoretical coherence
Full-line: correlated samples generator
Coherence estimator

Bias for $L=10000$ looks is extremely small.
For any biased estimated coherence, unbiased coherence could be potentially estimated (using the figure below).

Observed coherence bias in the range of $0.02 - 0.03$
At this range, negligible offset due to MLE
Observation of CCP over other media

-> Analysis over Uyuni (isotropic media with no azimuthal backscattering dependency)

with polarimetric calibration, VVVH phase centered at about 0°