Cross-Polarized Synthetic Aperture Radar: A New Potential Measurement Technique for Hurricanes

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SAR wind speed retrieval

\[ \sigma_0(\theta, U_{10}, \phi) = A_0(\theta, U_{10})[1 + A_1(\theta, U_{10}) \cos \phi + A_2(\theta, U_{10}) \cos(2\phi)]^{1.6} \]
 Movitation

Wind direction

- SAR image itself
- Weather prediction model
- Scatterometer observations

limitations
NRCS_VV dependent on incidence angle and wind direction
RADARSAT-1 \rightarrow \text{“the past”}

only HH-polarization data...
2. Wind blending for conventional algorithms

Co-Polarization Model: CMOD5.N

\[ \sigma_{0}^{(m)} = B0(1 + B1 \cos \phi + B2 \cos 2\phi)^{1.6} \]

\[ B1 = \frac{c_{14}(1 + x) - c_{15}v(0.5 + x - \tanh[4(x + c_{16} + c_{17}v)])}{1 + \exp(0.34(v - c_{18}))} \]

\[ B2 = (-d_{1} + d_{2}v_{2}) \exp(-v_{2}) \]

1: Wind speed, wind direction and radar incidence angle dependence.

2: NRCS_VV saturates at high winds.

- the wind speed ambiguity problem in SAR Imagery
NRCS under high winds

Donelan et al.

Incident angle = 35°
- Donelan et al. (2004)

Incident angle = 31°
- Fernandez et al. (2006)
Wind retrieved from self-simulated NRCS VV polarization

CMOD5

COMD4HW

HWGMF_V

HWGMF_H

smaller solution

bigger solution
How to remove speed ambiguity?

- Neither smaller solution OR bigger solution can be taken directly as the real wind.
Speed ambiguity removal for hurricanes

- A typical hurricane wind profile

from Holland (1980) profile
Ambiguity in hurricane speed profile

![Graph showing wind speed profile with radial distance](image_url)
Speed ambiguity removal

SAR NRCS for hurricane

Wind direction

Ambiguous winds

Pixel to eye distance

Threshold positions

ambiguity removal criteria / quadrant

Final winds

Speed ambiguity removal method
Speed ambiguity removal for Rita
→ Envisat ASAR image (Sep 22 03:22 2005)
Wind retrieval

- Smaller ambiguous solutions

Wind direction was taken as the tangential angle with 20° inflow angle
Wind retrieval

- Bigger ambiguous solutions

Wind direction was taken as the tangential angle with 20º inflow angle.
After ambiguity removal
Speed difference with NHC winds

Smaller solution - NHC winds
Speed difference with NHC winds

Final solution - NHC winds
Conclusions to here - 1

1) ambiguity exists in high wind SAR retrievals, more severe at near side of SAR range
2) based on typical cyclone structure, a speed ambiguity removal method is developed
3) method can maybe be generalized and adopted to other GMFs to give improved SAR retrieved winds.

The present – RADARSAT-2

Imaging Modes

Launched – Dec 2007

HH, VV, HV, VH polarization data...
The present – RADARSAT-2

**Motivation**

C-2PO

NRCS_VH \[\rightarrow\] Independent of incidence angle and wind direction
Polarimetric correlation coefficient between VV and HV

\[
\rho_{VVHV} = \frac{\langle S_{VV} \cdot S_{HV} \rangle}{\sqrt{\langle |S_{VV}|^2 \rangle \langle |S_{HV}|^2 \rangle}}
\]

Scattering matrix

\[
S = \begin{bmatrix}
S_{hh} & S_{hv} \\
S_{vh} & S_{vv}
\end{bmatrix}
\]

RS - 2 Fine Quad-Polarization
NRCS in cross-polarization versus relative wind direction
Real part of Polarimetric correlation coefficient (PCC)

Odd symmetry
Results

Imagery part of Polarimetric correlation coefficient (PCC)

odd symmetry
Wind-vector retrieval algorithm (our idea)

Method

→ solve ambiguity problem
Wspd=15.7 m/s  Wdir=169°

Mar 20, 2010  04:33 UTC
Buoy-measured wdir=169°
Our Retrieved wdir=151°

Buoy-measured wspd=15.7 m/s
Our Retrieved wspd=13.7 m/s
Wspd=19.0 m/s  Wdir=142°

Jan 09, 2011  05:15 UTC
Buoy-measured $\text{wdir}=142^\circ$
Our Retrieved $\text{wdir}=152^\circ$

Buoy-measured $\text{wspd}=19.0\text{m/s}$
Our Retrieved $\text{wspd}=17.8\text{ m/s}$
Wspd=11.1 m/s   Wdir=311°
Buoy-measured wdir=311°
Our Retrieved wdir=323°

Buoy-measured wspd=11.1 m/s
Our Retrieved wpsd=10.3 m/s
odd / even symmetries of polarimetric correlation coefficients (PCC) for co- / cross-polarizations → remove wind ambiguity.

we propose a retrieval algorithm for wind speed + direction simultaneously based on C-2PO, CMOD5.N for quad-pol data.

1) Zhang, B., Perrie, W., Vachon, P. Li, X., Pichel, W., 2012: Ocean Vector Winds Retrieval from C-band Fully Polarimetric SAR Measurements. In press *IEEE TGRS*

3. SAR-wind models

NRCS_VV, NRCS_HH depend on incidence angle, wind direction

NRCS_VH, NRCS_VH not sensitive to incidence angle, wind direction

Quad-Polarization Ocean Backscatter data

NRCS_VV saturates

no NRCS_HV saturation

C-band Cross-Polarization model: C-2PO

\[ \sigma_{VH}^0 = 0.580 * U_{10} - 35.652 \]
Hurricane wind-speed retrievals with C-2PO

SAR-derived wind map from C-2PO model and RADARSAT-2 Hurricane Bertha image acquired on July 12, 2008 at 10:14 UTC

Hurricane Bertha – 12 July 2008
SAR-derived wind map from C-2PO model and RADARSAT-2 Hurricane Ike image acquired on Sep 10, 2008 at 23:54 UTC

Hurricane Ike – 10 Sept 2008
Hurricane Danielle – 28 Aug 2010
Hurricane Earl on Sep 02, 2010 at 22:59 UTC

RADARSAT-2 dual-polarization SAR image
Fig. 3. One RADARSAT-2 dual-polarization SAR image acquired over Hurricane Earl at 22:59 UTC on September 2, 2010, (a) VV polarization and (b) VH polarization. Colorbar show sigma-naught in VV polarization ($\sigma_{VV}^0$) and in VH polarization ($\sigma_{VH}^0$) in dB, respectively. SAR-retrieved wind speeds from (c) the CMOD5.N model and $\sigma_{VV}^0$, with external wind directions from NOAA HRD H*Wind are overlaid, and (d) from the C-2PO model and $\sigma_{VH}^0$. Colorbar shows wind speeds at 10-m height ($U_{10}$) in m/s. RADARSAT-2 Data and Products © MacDonald, Dettwiler and Associates Ltd, - All Rights Reserved.
Comparison of C-2PO and CMOD5. SAR wind retrievals

Along track-SFMR (hr) time series

SFMR-measured 10s rain rates (mm/hr) time series (hr)

rain? high waves, eyewall gradients…?
Comparisons of C-2PO and CMOD5.N SAR-retrieved winds U10 (Sep 02, 2010 at 22:59 UTC) with collocated H*Wind
Wind speed from NDBC buoy #41001 is 18.1 m/s
from C-2PO model is 16.0 m/s
from CMOD5.N is 17.4 m/s
from H*Wind is 16.8 m/s
Hurricane Ike

dual-polarization SAR image at 23:56 UTC on Sep 10, 2008

VV polarization  VH polarization

CMOD5.N + wind directions via H*Wind

C-2PO model U10
Comparisons of C-2PO and CMOD5.N SAR-retrieved winds U10 (23:56 UTC, on September 10, 2008) with collocated H*Wind

CMOD5.N → bias of -4.89 m/s and RMS error of 6.51 m/s
C-2PO → bias of -0.88 m/s and RMS error of 4.47 m/s
The future - coordinated international constellation of SAR Winds satellites?
Conclusions – part 3

- C-2PO model presented
- insensitive to wind direction, radar incidence angle
  - easy mapping of observed cross-pol NRCS to wind speed
- avoids errors in wind speed retrievals that occur in CMOD5.N
- in quad-pol data, C-2PO does not seem to saturate
  - potential for hurricane wind retrievals
- dual-pol Earl: high wind verification of R2 SAR – airborne SFMR