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# Wind speed estimation using C-band compact polarimetric SAR for wide swath imaging modes

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## ABSTRACT

We have investigated the use of C-band compact polarimetric synthetic aperture radar for estimation of ocean surface wind speeds. Using 1399 buoy observations collocated with Radarsat-2 scenes, compact polarimetric data was simulated for two of the Radarsat Constellation's planned wide swath imaging modes. Provided the wind direction is known or can be estimated, our results demonstrate that wind speed can be estimated from the right-vertical polarization channel of the compact polarimetry using a combination of the CMOD5 geophysical model function and a linear model. If wind speed estimation without wind direction input is desired, the randomly-polarized component of the backscattered power can be used in a similar fashion to that of the linear cross-polarizations, but is less affected by increases in the noise effective sigma-zero of the data. A model is proposed for the randomly-polarized power as a function of incidence angle and wind speed, independent of wind direction. The results suggest that compact polarimetry is a strong alternative to linearly polarized synthetic aperture radar data for wind speed estimation applications, particularly for wide swath imaging modes with a high noise floor.

## 1. Introduction

The estimation of ocean surface winds from space is an important area of remote sensing research, with applications such as hurricane forecasting, wind energy mapping, estimation of oil spill drift patterns, and in the validation and development of numerical weather prediction (NWP) models, among other uses. Estimating ocean winds using scatterometer and synthetic aperture radar (SAR) data is possible due to the fact that the wind exerts a shear stress (known as wind stress) on the ocean, which stimulates the roughness of the ocean surface, therefore increasing the observed backscatter.

The most common wind speed estimation methods using C-band SAR are in the form of geophysical model functions (GMFs) which yield normalized radar cross-section (NRCS) values, denoted by the symbol $\sigma^0$, as a function of parameters such as incidence angle, wind speed, and wind direction. One of the most popular GMFs in recent usage is CMOD5, a robust model developed by Hersbach et al. (2007) using C-band scatterometer measurements from the satellite ERS-2. CMOD5 allows VV polarization NRCS to be calculated as a function of incidence and azimuth angle, wind speed, wind direction, and a set of 28 constant parameters. When working with SAR data, the NRCS and the incidence and azimuth angles are known, while the wind speed and/or wind direction (Portabella et al., 2002) needs to either be obtained from external sources (such as weather buoys, scatterometers, or NWP models), or estimated from the SAR image itself. Combining SAR data with NWP models can provide a fairly robust estimate of the wind vector (Portabella et al., 2002). Wind direction can also be estimated from the SAR image by detecting the orientation of wind streaks in the image (Wackerman et al., 1996; Du et al., 2002). This can be done using the discrete Fourier transform (Wackerman et al., 1996) or through wavelet analysis (Du et al., 2002), among other methods.

Unfortunately, when estimating wind direction from SAR images, there is an inherent 180 degree ambiguity due to the fact that the wind runs roughly parallel with the wind streaks, but the direction the wind is traveling along the streak is unknown. This ambiguity can be resolved, such as through the use of NWP models (Carvajal et al., 2014), but is still an obstacle when attempting to estimate the wind vector from radar backscatter (Portabella et al., 2002). Estimating the wind direction can also be problematic near land or sea ice (Komarov et al., 2014). Another limitation of using co-polarized (co-pol) backscatter for wind speed estimation is that both VV and HH $\sigma^0$ values become saturated at higher wind

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speeds, making estimation of wind speeds greater than 15–20 m/s unreliable (Donnelly et al., 1999).

While the CMOD5 GMF models VV polarization backscatter only, if the VV polarization is not available, the HH polarization can be used to estimate the VV polarization using published models for the co-polarization ratio (the ratio of VV $\sigma^0$ to HH $\sigma^0$) (Vachon and Wolfe, 2011; Vachon and Dobson, 2000; Zhang et al., 2011; Mouche et al., 2005). The modeled VV $\sigma^0$ corresponding to the observed HH $\sigma^0$ can be calculated and then used in the CMOD5 GMF as normal.

While co-pol backscatter is heavily dependent on wind direction, it has been shown that cross-polarized (cross-pol) backscatter is less dependent on wind direction and incidence angle (Vachon and Wolfe, 2011; Hwang et al., 2010; Zhang and Perrie, 2012; van Zadelhoff et al., 2014). While recent work has shown that both the HV and VH polarizations do in fact exhibit some dependence on incidence angle and wind direction, and that these relationships are most clear at high signal-to-noise ratio (SNR) values (Hwang et al., 2014), results have shown that high wind speed estimation accuracy can still be achieved without wind direction input (Vachon and Wolfe, 2011; van Zadelhoff et al., 2014). Vachon and Wolfe (2011) developed an empirical linear relationship between the cross-pol $\sigma^0$ (in dB) of Radarsat-2 fine-quad data and wind speed, yielding smaller wind speed estimation errors than CMOD5 for their dataset.

Another advantage of wind speed estimation using cross-pol data is that the cross-pol data do not saturate for wind speeds greater than 15–20 m/s as do the co-pol data. Cross-pol data have been observed to begin saturating at wind speeds in excess of 30 m/s, for incidence angles of 30–40 degrees (Hwang et al., 2014). This makes cross-pol wind speed estimation particularly useful for applications relating to hurricanes and other high wind speed events (van Zadelhoff et al., 2014).

Unfortunately, the main limitation of cross-pol data is its low SNR—cross-pol $\sigma^0$ can often be an order of magnitude smaller than co-pol $\sigma^0$. For Radarsat-2 fine-quad mode data, this is not a significant issue due to the very low noise equivalent sigma-zero (NESZ) of these data (nominally −36 dB), and the small amount of crosstalk (Vachon and Wolfe, 2011). However, for many other SAR sensors and imaging modes with higher NESZ values, and/or greater amounts of crosstalk, the cross-pol channels can be dominated by noise effects at low wind speeds, making accurate wind speed estimation difficult. While the Radarsat-2 fine-quad mode provides excellent noise characteristics, it also has a small swath width (25 km), which is not ideal for maritime applications. Unfortunately, most wide swath imaging modes also have higher NESZ values. Because of this, Shen et al. (2014) proposed the use of a piecewise linear model to relate the cross-pol $\sigma^0$ of dual-pol Radarsat-2 ScanSAR data to wind speed. Their function has a shallow slope for wind speeds less than 10.1 m/s, where the cross-pol $\sigma^0$ is dominated by noise, and a steeper slope for wind speeds above 10.1 m/s. Unfortunately, for wind speeds below 10.1 m/s, the error in the estimated wind speeds was quite large. Komarov et al. (2014) also proposed a method to mitigate the low SNR of cross-pol data, with a polynomial model that used both the HH and HV channels of dual-pol Radarsat-2 ScanSAR data to estimate wind speed independent of wind direction. When the HV backscatter was sufficiently above the nominal NESZ (as recorded in the metadata), the HV backscatter was used in combination with the HH backscatter. For low wind speeds where the HV backscatter was dominated by noise, only the HH polarization was used. Unfortunately, this means that for low wind speeds, the wind direction dependence of the HH polarization must be ignored when using this model, reducing the potential accuracy of these low wind speed estimates.

The discussion so far has centered around the various widely available linear polarization combinations—VV, HH, HV, and VH. In recent years, there have been a number of proposals regarding the use of compact polarimetry for remote sensing of the Earth (Raney, 2007; Souyris et al., 2005; Stacy and Preiss, 2006). Compact polarimetry comprises a number of dual-pol SAR configurations that utilize a transmit polarization other than the linear horizontal or vertical. The next generation of Canada's Radarsat program, the Radarsat Constellation Mission (RCM) (Canadian Space Agency, 2013), will be a set of three satellites capable of collecting C-band compact polarimetric data in the circular transmit, linear receive (CTLR) or hybrid-polarity imaging mode (Raney, 2007). In this mode, the transmitted polarization is circular (right-circular in the case of the RCM), while the received polarization basis is the familiar linear horizontal and vertical, yielding the two polarization channels RH (right-horizontal) and RV (right-vertical) (Raney, 2007). Neither the RH or RV channel is co-polarized or cross-polarized in the traditional sense, since the transmitted and received polarization bases are different (Raney, 2007)—therefore, each of these channels can be thought of as containing a mixture of co-pol and cross-pol linear backscatter (see Section 2.2). The RCM, planned to launch in 2018 (Canadian Space Agency, 2013), will collect CTLR data in a variety of wide swath imaging modes well suited for use in maritime surveillance applications.

In this paper, we explore the use of CTLR compact polarimetry for wind speed estimation, using Radarsat-2 fine-quad mode data to simulate both linear and compact polarimetric data in two of the planned RCM imaging modes: the low noise mode (with nominal NESZ of −25 dB) and the low resolution mode (with nominal NESZ of −22 dB). We chose these modes for analysis in order to assess the wind speed errors of a number of different estimation methods across a range of NESZ values. First, we combined CMOD5 with Vachon and Wolfe's linear model for cross-pol $\sigma^0$ (Vachon and Wolfe, 2011) in order to estimate wind speed from the RV channel (by considering the RV channel as the sum of VV and HV backscatter). Then, we attempted to approximate the linear NRCS values of the VV and HV polarizations from the compact polarimetric data using a process known as pseudo quad-pol reconstruction (Souyris et al., 2005; Nord et al., 2009; Collins et al., 2013). We used the pseudo-VV as input to CMOD5, and the pseudo-HV as input to a linear model.

Finally, we investigated the use of the randomly-polarized component of the CTLR backscattered power, calculated using the Stokes parameters (Raney, 2007, 2006; Lee and Pottier, 2009). We developed a basic empirical model that relates this randomly-polarized power, or RPP, to incidence angle and wind speed. While the RPP has some dependence on wind direction, this dependence is fairly small (see Section 3.6), similar to the linear cross-pol $\sigma^0$, such that we ignored it in favor of allowing wind speed estimation in the absence of wind direction input. We also found that wind speed estimation using the RPP was less effected by the increased NESZ of the simulated RCM imaging modes than the linear cross-pol methods. This suggests that CTLR data can be a viable choice for wind speed estimation without wind direction input, in situations where the SNR of the linear cross-pol backscatter is too low for accurate wind speed estimation of low to moderate wind speeds.

## 2. Data

### 2.1. Buoy processing

The dataset used in this study was provided to us by Paris Vachon and John Wolfe of Defence Research & Development Canada. These data consisted of 1644 buoy observations which