Assessment of Ocean Wind Retrieval from Dual-Polarized X-band SAR data

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Abstract

Assessment of wind speed retrieval from dual-polarized X-band SAR data is performed using geophysical model functions for the normalized radar cross-section (NRCS) and the Doppler frequency. It is shown that the retrieved wind speed accuracy is similar for VV (standard deviation of 2.33 m/s) and HH (standard deviation of 2.32 m/s) polarizations. The geophysical Doppler model is used to assess the potential of using the polarization residual (VV-HH) Doppler frequency (PRDF) estimated from dual-polarized SAR data, in future wind speed retrieval algorithms. A correlation of 0.79 is achieved between the in situ radial wind speed component and the estimated PRDF.

1 Introduction

Wind retrieval over the sea surface is a critical element of weather forecasting, ship routing, and ocean climatology. This operation has been made possible on a large scale thanks to both scatterometry and SAR technologies. The use of the latter has the major advantage of very high resolution. Both technologies currently require however the use of semi-empirical geophysical model functions (GMFs) to infer wind information from their respective backscatter signals. These GMFs are designed to provide optimal results with scatterometers for a chosen frequency band; in the C-band operating frequency range, the CMOD5 GMF is currently used along with ASCAT [1]; in the Ku-band range, both QMOD3 and QMOD4 were used along with QuikSCAT [2]. These semi-empirical GMFs can be used for SAR wind retrieval applications, though some limitations may be encountered due to drastic resolution difference between GMFs and SAR products. [3] and [4] show two different approaches at developing semi-empirical GMFs in the X-band range specifically for SAR applications. Furthermore, the use of the Doppler anomaly, as defined in [5], has been proposed as an additional metric in wind retrieval.

In [6] and [7], purely theoretical GMFs are derived for NRCS and Doppler frequency computations (referred to as GCM-NRCS and GCM-Dop, respectively) based on the Generalized Curvature Ocean Surface Scattering Model (GCM). Since their building blocks are strictly theoretical, the use of these GMFs is neither restricted to a specific operating frequency band, incidence angle, nor polarization. To this date, only validation of the GCM-NRCS has been performed against C-band data [8]. The objectives of this paper are to first further validate both GMFs by analyzing their respective performance against X-band data, using the polarization ratio ($\sigma^o{}_{VV}/\sigma^o{}_{HH}$) and the polarization residual Doppler frequency (PRDF); second the wind signature in the PRDF is evaluated and the accuracy of wind retrieval from TerraSAR-X backscatter data in both HH and VV polarizations is assessed using the GCM-NRCS model.

2 GCM Performance Analysis

When a SAR instrument transmits an FM pulse over the sea surface, the signal received can be modeled by the convolution of the ocean surface reflectivity with the SAR impulse response of a point target. The raw SAR data can then be compressed, and NRCS as well as Doppler centroid can be computed from it using the method of moments [7]. As part of this simulation, a model for the ocean surface reflectivity is required. The GCM provides the backbone of this source function [6].

In order to compute both X-band NRCS and Doppler centroid using the GCM, both geophysical and instrument related parameters are required as inputs such as: wind speed and direction, inverse wave age (ratio of wind speed to wave speed), radar operating frequency, polarization, and radar incidence angles. Once all these variables are fed to the model, NRCS and Doppler centroid are computed using the methodology described in [7]. The next two subsections provide validation results of these two metrics against TerraSAR-X data.

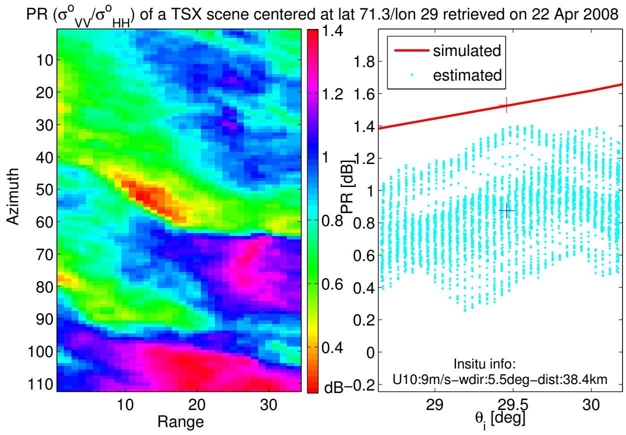

Figure 1: The 2-D plot (left) shows the PR distribution, while on the right the estimated and simulated PRs are plotted against the incidence angle. A small bias is present between the simulated and the estimated PRs as well as a an apparent strong correlation. Note the mean NRCS values shown on the right plot.

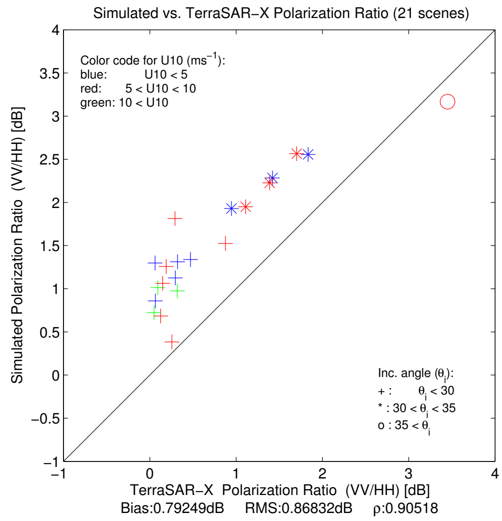

Figure 2: Scatterplot of the simulated vs. estimated TerraSAR-X PR for 21 scenes. Note a high correlation (0.91) between the two datasets, albeit a noticeable 0.79 dB bias.

2.1 GCM-NRCS analysis

When working with dual-polarized data, the polarization ratio (PR) is a quantity commonly used to convert semi-empirical GMF σ^o from one polarization to another. Therefore, it is of our interest to measure the GCM-NRCS performance at X-band using the PR. To do so, 21 TerraSAR-X ocean scenes (collected in dual polarization stripmap mode) are carefully selected over the Norwegian sea, in proximity to in situ weather data (within a 160km radius). Each scene is broken down into 1x1km cells, in which NRCS is estimated and recorded for a given polarization and incidence angle. Spatial and temporal collocations are performed with in situ weather stations. For each collocated scene, both NRCS and incidence angle are averaged over the whole scene. These two variables are then combined with local true wind information to be used in combination with the GCM-NRCS.
To illustrate this analysis, figure 1 shows a 2D PR profile (left) as well as the PR versus the incidence angle (right) for a single TerraSAR-X scene retrieved on 22 April 2008. There are two noticeable features in these plots: an existing correlation between the simulation and the estimated PR (right) with the presence of a small bias, and the expected PR increasing trend with increasing incidence angle. Note the mean NRCS values shown on the right plot of figure 1 for both estimated and simulated datasets. These are the values recorded for each collocated scene and eventually combined for further PR analysis. Figure 2 shows a scatterplot of the simulated versus estimated PR for all 21 TerraSAR-X scenes. Color-coding and various symbols have been used to classify results according to wind speed and incidence angle, respectively. Note a small bias of 0.79 dB as well as a strong correlation (0.91) between the two datasets. The results of this analysis are important as it shows that the GCM-NRCS is capable of predicting polarization dependency in the NRCS given wind conditions, not only for a C-band platform [7], but also for an X-band platform.

2.2 GCM-Dop analysis

We are now interested in performing a very similar analysis with the Doppler information instead. For a given scene, the Doppler centroid is estimated for each 1x1km cell. This task involves a simple two-step-process: first the azimuth Fourier spectrum is computed for a given cell; second, the Doppler centroid is estimated by fitting a Hanning window (with a 0.6 factor) to the azimuth Fourier spectrum. This process is run in each cell for each channel. Once the estimations are done, the difference between the VV and HH Doppler centroids for each cell is computed. This metric is called the polarization residual Doppler frequency (PRDF). Analyzing this metric has the major advantage of highlighting the geophysical contribution to the Doppler signal by eliminating the geometric Doppler contribution and possibly reducing antenna mispointing errors. As with the NRCS analysis, the PRDF is averaged over the whole scene and associated with a local mean incidence angle and local true wind data. These variables (except for the PRDF) are inputted to the GCM-Dop to model PRDF values. As an illustration, figure 3 shows how the PRDF varies over a given scene retrieved on 22 April 2008. On the left plot, an interesting effect is noticeable along the azimuth direction: the image appears to be divided into three horizontal equal portions. This pattern is present in several of the 21 TerraSAR-X scenes, which may be a problem due to the azimuth processing window (Hamming window) used in the TerraSAR-X Multimode SAR Processor

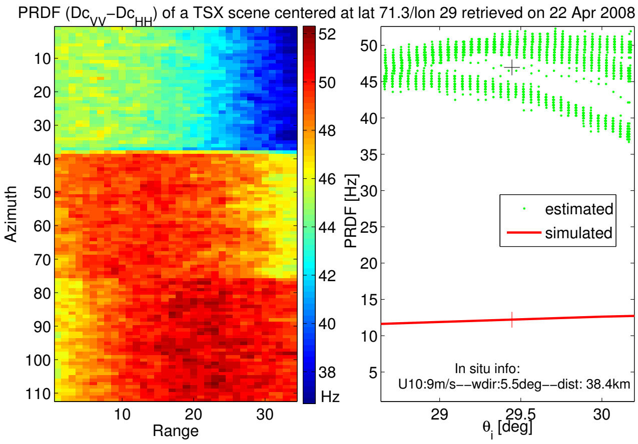

Figure 3: 2-D PRDF plot (left) and scatterplot (right) of the PRDF vs. incidence angle for a given scene. Note how the PRDF seems to be divided into three equal portions (left) in the azimuth direction, probably due to the use of a Hamming window in the TMSP. Furthermore, a clear bias most likely caused by antenna steering issues, is also present between simulated and estimated PRDFs (right).

(TMSP); this filter implementation modifies the original spectrum and may negatively impact the Doppler analysis [9]. The right plot shows the PRDF vs. the incidence angle. A strong bias ($\sim$ 38Hz) is also present between the simulated and estimated PRDFs. This bias is consistently found in all 21 scenes. To identify the source of it, Doppler centroids from dual polarized stripmap TerraSAR-X land scenes from various latitudes on the globe have been analyzed. No bias is present for scenes centered at low latitude. As the latitude increases, the bias increases. As a result, it has been concluded that this artifact is most likely due to a problem in the antenna steering pointing accuracy between polarizations.

Figure 4 shows a scatterplot of the simulated versus estimated PRDF for the same 21 TerraSAR-X scenes. Here the estimated PRDFs have been bias corrected. There is a high correlation coefficient of 0.84 between the two datasets. This result indicates that there must also be a correlation between the estimated PRDF from the TerraSAR-X scenes and the local wind field. To verify this claim, figure 5 shows estimated and simulated PRDFs, both, vs. radial in situ wind speeds. As predicted, the estimated PRDF is strongly correlated with radial in situ wind speed. We can conclude that it can be possible to extract wind information using TerraSAR-X Doppler frequencies.

3 Wind speed retrieval

The GCM-NRCS is now used to retrieve wind speed from TerraSAR-X NRCS for both HH and VV polarizations. The NRCS from the GCM-NRCS is a function of incidence angle, wind direction, wind speed, polarization,

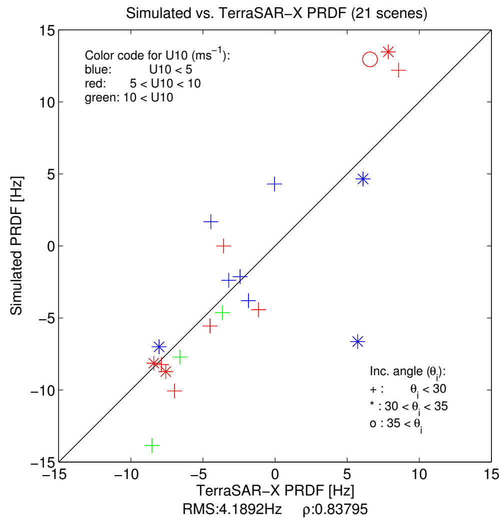

Figure 4: Scatterplot of the simulated vs. estimated TerraSAR-X PRDF for all 21 scenes. Note once again a high correlation between the two datasets. Since the simulated PRDF is dependent on the radial wind speed, it can be concluded that PRDFs estimated from TerraSAR-X dual-pol. data contain information on the wind speed.

and inverse wave age. For a given polarization, inverse wave age, wind direction and incidence angle, the wind speed can be retrieved knowing the NRCS. Using previously estimated mean TerraSAR-X NRCS and the corresponding in situ wind direction, wind speeds are then successfully retrieved using the GCM-NRCS and compared with actual in situ values. Figure 6 shows a scatterplot of the retrieved wind speeds from TerraSAR-X σ^o_{HH} (red scatterplot) and σ^o_{VV} (green scatterplot). The standard deviations for both datasets are very similar and fairly small (2.33 m/s for HH and 2.32 m/s for VV). Correlations are also strong for both polarization, and biases are almost non-existent. A similar analysis is performed using a semi-empirical X-band GMF (XMOD) developed by Mouche et al. [3] instead of the GCM-NRCS, to retrieve wind speed from TerraSAR-X NRCS data. Similar biases are obtained (0.6m/s–HH, 0.75m/s–VV), with smaller standard deviations (1.95m/s–HH, 1.96m/s–VV) and slightly improved correlations (0.81–HH, 0.80–VV). The slightly larger standard deviations and lower correlations obtained with the GCM-NRCS, compared with the XMOD, may be due to the lack of sufficient skewness in the sea surface wave description implemented and described in [6]. Despite this current limitation, results shown from figure 6 strongly indicate the GCM-NRCS as a valid candidate in sea surface wind retrieval from radar backscatter signals.

4 Conclusion

Analysis and performance of both GCM-NRCS and GCM-Dop GMFs have been assessed with respect to wind retrieval from dual-polarized X-band SAR data. 21 Terra-

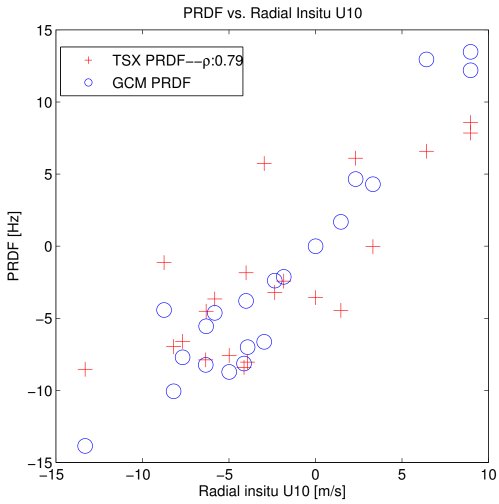

Figure 5: Scatterplot of both estimated and simulated PRDFs versus radial in situ wind speed. The estimated PRDF is strongly correlated with in situ wind speed which clearly shows its strong wind dependency. Negative radial in situ wind speeds correspond to upwind and positive correspond to downwind wrt radar antenna.

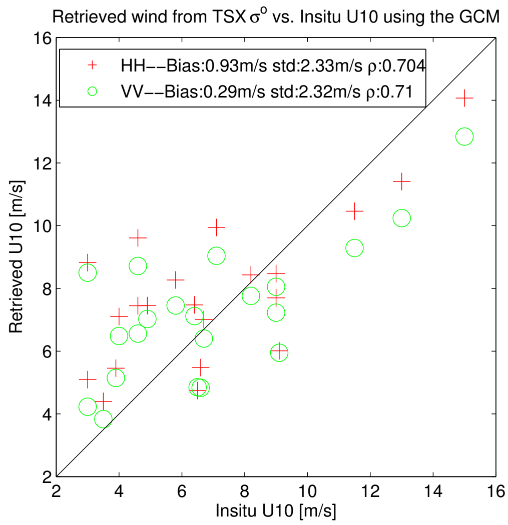

Figure 6: Scatterplot of retrieved versus in situ wind speeds for both HH and VV polarizations. The retrieved wind speeds are derived from TerraSAR-X σ^o_{HH} and σ^o_{VV}. Note similar standard deviations for both polarizations.

SAR-X scenes were used to evaluate their respective performance at computing NRCS and Doppler centroid. A few artifacts were noticeable in the TerraSAR-X products used, where antenna steering issues may have affected the Doppler signal. Nevertheless, strong correlations exist between simulation and actual estimated data. The PR analysis with TerraSAR-X data provides very similar results obtained with ASAR AP data described in [8], except for a slightly larger bias (0.79dB vs. 0.16dB). A strong wind dependency is shown to be present in the estimated PRDF. Wind speed retrieval from TerraSAR-X backscatter data at both HH and VV polarizations was performed using the GCM-NRCS. Wind speeds retrieved at both polarizations agree well with the actual in situ wind speeds. These results reinforce the use of the GCM based GMFs in sea surface wind retrieval from radar backscatter signals. Future work will include developing wind retrieval algorithm which incorporates both the dual-polarized NRCS and the PRDF to help solve for wind direction ambiguities, such that use of auxiliary wind direction resources is less important. Further improvements could be made to the sea surface description implemented in the actual GCM, particularly the skewness factor.

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