An Improved High Resolution Wind Ambiguity Removal Procedure for SeaWinds

Brent A. Williams and David G. Long
Brigham Young University, Microwave Earth Remote Sensing Laboratory
459 Clyde Building, Provo, UT 84602 USA

***Abstract*— The SeaWinds scatterometer was developed to measure ocean surface winds from space at a resolution of 25 km. Recently, a higher resolution (2.5 km) SeaWinds product has proven useful in several applications. However, high resolution wind field estimates are very noisy and this complicates ambiguity selection. The current high resolution ambiguity selection procedure is initialized (or nudged) by the low resolution (L2B) result which may not produce sufficiently accurate results. This paper describes an entirely new method for initializing scatterometer wind ambiguity selection, especially for high resolution winds. This initializing field is obtained by spatially filtering enhanced resolution backscatter measurements, retrieving the wind, and then correcting inconsistencies in the resulting first ambiguity wind field. For nudging, this field is comparable in quality to the numerical weather prediction (NWP) estimates, and is used independent of the NWP winds to nudge the high resolution ambiguities and produce improved wind field estimates.**

I. Introduction

SeaWinds indirectly measures ocean surface winds. It directly measures the normalized radar cross section of the surface (σ_0), which over the ocean is related to the wind via the geophysical model function (GMF). After the instrument measures values of σ_0 from multiple azimuth angles, the σ_0 measurements are processed to estimate the ocean surface wind speed and direction. Wind retrieval is done by maximizing a maximum likelihood (ML) objective function using the σ_0 measurements over each individual resolution cell. At each resolution cell, up to four possible wind vector solutions result, ordered by their ranking likelihood value. An ambiguity selection procedure is then performed to select a single vector estimate of the wind.

Conventionally, winds are retrieved at a resolution of 25 km, but the dense spatial sampling provided by SeaWinds makes it possible to retrieve wind at a much higher resolution by using reconstruction/resolution enhancement techniques. These techniques provide σ_0 data posted on a much finer scale (2.5 km) from which conventional wind retrieval is performed [1]. These high resolution fields, although more noisy than the low resolution (L2B) result, have proven useful in several applications including hurricane and storm tracking [1].

High resolution wind retrieval also results in four possible wind vector solutions at each resolution cell—requiring an ambiguity selection algorithm. Common ambiguity selection techniques are iterative methods—they start with an initial guess and repeatedly process the data until the solution converges. To be effective, such techniques require an initial guess close to the optimum solution. Several ambiguity removal methods use external data to "nudge" (or initialize) the ambiguity selection process [2]. Currently, the high resolution ambiguity selection method is initialized with the L2B result, which may not be sufficiently accurate.

This paper describes an entirely new method for initializing scatterometer wind ambiguity selection, especially for high resolution winds. The new method is analyzed using both real data and simulation. Some limitations and future improvements of the method are considered.

II. Method

The new method improves the high resolution ambiguity selection by obtaining a high quality nudging field from the scatterometer data. This field is obtained by processing the 25 km resolution σ_0 fields to 2.5 km resolution [1], spatially low-pass filtering the high resolution σ_0 fields, retrieving the wind, and then correcting the remaining directional inconsistencies in the ML first ambiguity field. The resulting wind field is used to initialize median filter based ambiguity selection for the high resolution ambiguities. Figure 1 illustrates the overall procedure.

A. Resolution Enhancement

For the new method, the first step in obtaining a high quality nudging field is to enhance the resolution of the σ_0 fields obtained by the scatterometer. This paper employs the method described in [1] to improve the spatial resolution to 2.5 km for each of the four azimuth looks.

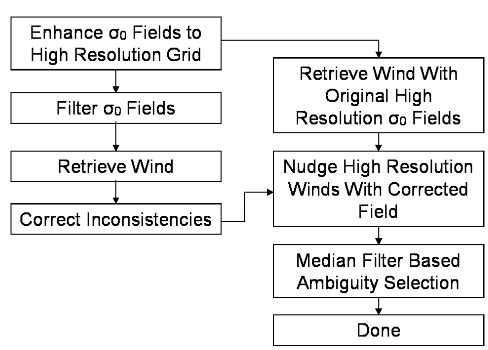

Fig. 1. Overall procedure of the new algorithm.

B. Backscatter Filtering

Given the enhanced resolution σ_0 fields, the first step to obtain an initializing field is to spatially low-pass filter or smooth each high resolution σ_0 field separately. This improves the variability of the ML estimate and results in a higher quality first ambiguity wind field.

A weighted averaging filter is used,

$$\hat{\sigma}_0(m,n) = \frac{\sum_{i,j=-s}^{s} W(m+i,n+j)\ \sigma_0(m+i,n+j)}{\sum_{i,j=-s}^{s} W(m+i,n+j)}, \tag{1}$$

where s controls the filter size and W is a weighting function that takes on the values of 1 if the measurement is over the ocean and 0 if it is over land. This ensures that measurements near coastal regions are not biased by land. Furthermore, the filter preserves the dense spatial sampling (2.5 km/vector) in order to aid high resolution nudging and promote a higher spatial correlation. Next, wind retrieval is performed on the smoothed σ_0 data at 2.5 km/pixel. This results in four ambiguities where the first ambiguity (ML wind estimate) is improved.

Several factors constrain the size of the low-pass filter. The power of the wind falls off approximately as k^{-2} [3]. Since the backscatter is proportional to magnitude of the wind squared, the backscatter falls off as approximately k^{-1}. Low-pass filtering the σ_0 fields destroys some high frequency information about the wind, thus degrading the resolution. Therefore, there is a trade-off between resolution and noise when choosing a filter size. However, by only using the lower resolution field to initialize a selection algorithm with the original high resolution ambiguities, the high resolution is preserved while constraining the result to be consistent with the low resolution estimate.

C. Inconsistency Correction

Even after filtering the σ_0 fields, the resulting ML first ambiguity wind field generally contains regions of directional discontinuities or inconsistencies. Therefore, the second step in the method is an inconsistency correction (IC) procedure. The IC procedure is similar to the method described by Draper and Long [4]; however, the dilation phase is modified to favor concave edges. The IC procedure begins by searching out and flagging inconsistencies in the σ_0-filtered ML wind field. After flagging the inconsistent vectors, a series of dilations and erosions are performed to flag inconsistent regions. The flagged regions are then flipped 180 degrees and the result is median filtered. This process is repeated until a maximum number of iterations is performed. The resulting field is smooth and more consistent. Thus, the new σ_0-filtering with inconsistency correction (SFIC) method produces a high quality nudging field for the high resolution ambiguities.

III. Analysis

Actual and simulated data are employed to explore the effectiveness of each phase of the algorithm and to choose tuning parameters. High resolution wind simulation is employed to provide a truth data set with which the results of the SFIC method can be compared.

In order to validate the method, the algorithm is also applied to various real data sets and compared with results obtained by the other techniques, including conventional low resolution winds and numerical weather prediction models. The new procedure produces more reliable high resolution wind field estimates.

A. Simulation

In order to determine error between the SFIC and the true winds, a high resolution geostrophic wind simulation is implemented. The synthetic "true" wind is derived by constraining the magnitude of the Fourier transform to fall off as k^{-2} and generating a random phase [5]. This synthetic wind field is used to simulate noisy σ_0 fields on which the new method is applied.

Simulation is utilized to determine the optimal parameter settings of the SFIC algorithm, and then the effectiveness of the procedure with the optimal parameter settings is tested extensively. The IC procedure is done on both the original high resolution and the filtered σ_0 wind fields. Table I shows the average percentage and RMS error of vectors closest to the simulated wind for several steps in the algorithm.

Filtering the σ_0 fields dramatically improves the skill (the percentage of vectors that are closest to the "true" wind) in high resolution retrieval from about 60% to about 80%. Although merely applying a median filter-based ambiguity selection procedure results in about the same percent of vectors closest to the true wind as performing the IC procedure (87 percent), the IC procedure reduces the RMS error, suggesting that the SFIC result is closer to the "true" wind. Finally, the SFIC high resolution result chooses about 88% of the ambiguities closest to the true wind.

These results assume a simple rain free geostrophic wind model and the results applied to real data may differ. However, the simulation suggests that the SFIC method is an appropriate method for high resolution ambiguity removal.

TABLE I

PERCENTAGES OF VECTORS CLOSEST TO THE TRUE WIND FIELD AND RMS ERROR FROM TRUE WIND FOR THE INNER PORTION OF THE SWATH (AVERAGED OVER 100 REALIZATIONS).

Category	Percent Closest	
	No σ_0 Filter	σ_0 Filter
1st Ambiguity (skill)	57.0 %	78 0%
Median filtered 1st ambiguity	66.5%	87.0 %
Inconsistency corrected	63.2 %	87.8 %
High resolution result	63.2 %	88.1 %
Category	**RMS Error**	
	No σ_0 Filter	σ_0 Filter
1st Ambiguity (skill)	24.5	17.3
Median filtered 1st ambiguity	23.8	12.0
Inconsistency corrected	23.1	9.5
High resolution result	23.1	12.1

TABLE II

Percentage of cells were SFIC method chooses the same high resolution ambiguities as nudging with the L2B or NWP winds.

	Percent Same			Total cells in bin
	L2B	NCEP	ECMWF	
S<5 m/s	90.5%	90.8%	96.2%	41450
5≤S<15 m/s	91.4 %	90.6%	90.2 %	1074136
S≥15 m/s	78.5%	78.4%	78.3 %	219530
All speed bins	89.9%	89.2%	88.9%	1335382

B. Validation

Lacking high resolution "truth" data for validation, the effectiveness of the algorithm is validated by applying it to several cases of real data and comparing the results with the low resolution L2B results and the Numerical Weather Prediction (NWP) winds. Two different weather prediction winds are used: the National Center for Environmental Prediction (NCEP) winds and the European Center for Medium-Range Weather Forecasting (ECMWF) winds. Both hurricane and non-hurricane cases are considered.

For regions not containing hurricanes, the SFIC algorithm is applied to several sets of QuikSCAT data and the results are compared to the L2B, NCEP and ECMWF winds for different wind speed regimes (less than 5 m/s, between 5 and 15 m/s, greater than 5 m/s, and all wind speeds). The percent of high resolution ambiguities closest to the L2B, NCEP, and ECMWF winds that are the same as the SFIC high resolution result are computed. Table II shows the results of the comparison and Figure 2 illustrates an example of the L2B and the SFIC results for a non-storm region and for a small storm.

About 89 percent of the SFIC high resolution winds are the same as the ambiguities closest to the model winds and the L2B winds. The L2B and NWP winds agree very well with the SFIC low resolution winds for typical wind speed regions (wind speeds less than 15 m/s), choosing about 90 percent of the same of the same high resolution ambiguities. For the stormy regions and regions of high wind speed the L2B winds differ from the SFIC winds; however, the difference is relatively small and both methods choose close to 80 percent of the same high resolution ambiguities. This suggests that the SFIC method produces a suitable nudging field for high resolution wind fields.

The difference between the SFIC winds and the L2B and NWP winds at high wind speeds could be due to several factors. The NWP estimates often spatially mis-locate storms and regions of high wind speeds. Furthermore, rain contaminates the scatterometer-derived wind estimates making the speed appear higher and modifying the direction; however, the σ_0 filtering may ameliorate this effect. Future investigation will consider how rain affects the σ_0-filtered ML estimate.

For hurricane cases, the NWP and L2B winds are compared with the SFIC winds along with characterizing features of the wind (such as the eye of a hurricane whose location can be determined strictly from the high resolution speed field). Figure 3 illustrates one hurricane example where the SFIC method produces a more accurate estimate of the hurricane eye than the L2B winds, although their remains a cross swath bias in some regions that is indicative of rain contamination. Thus, the SFIC method can improve the nudging field over the L2B winds even in storm and hurricane cases, but further investigation must be done to explore rain effects.

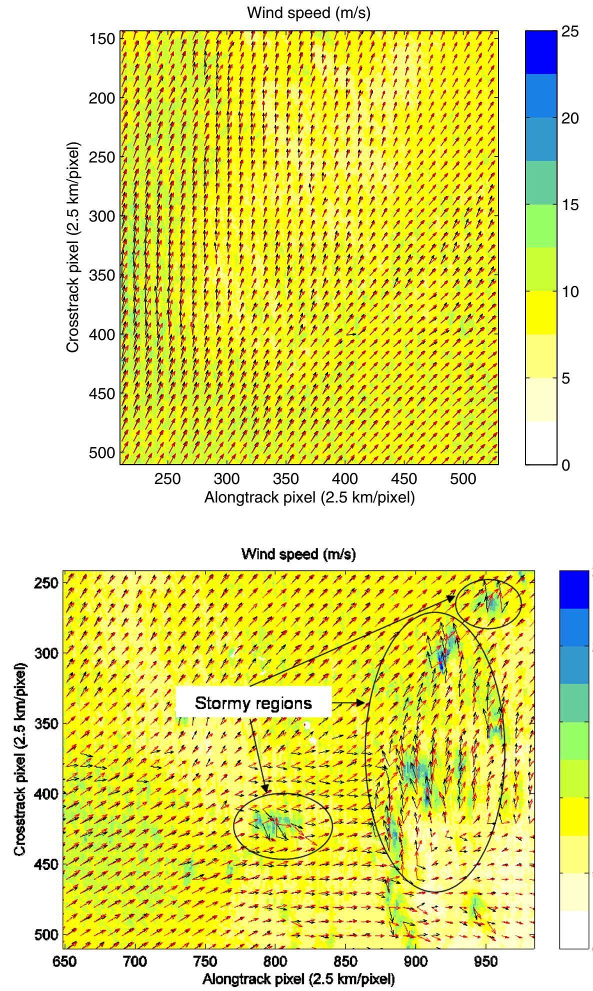

Fig. 2. L2B and SFIC low resolution results for a non-storm (top) and for a small storm (bottom) derived from σ_0 data obtained by QuikSCAT. The red vectors are the L2B winds, The black vectors are the down sampled SFIC low resolution winds. The SFIC low resolution result matches the L2B result very well everywhere but in the stormy regions where rain could be contaminating the ML estimate of the filtered σ_0 fields.

IV. Conclusion

Backscatter filtering combined with inconsistency correction can produce high quality initializing fields for ultra high resolution ambiguity selection that are independent of external data. Filtering the backscatter fields improves the high resolution ML estimator because it reduces noise. However, even in a noise-free environment, inconsistencies complicate ambiguity removal. Fortunately, these inconsistencies have structure and can often be corrected.

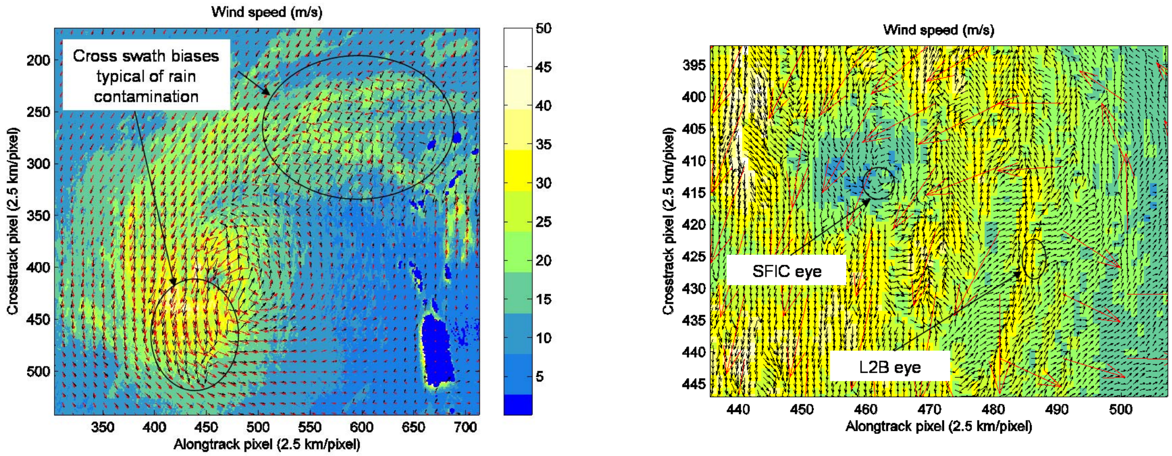

Fig. 3. Hurricane Floyd example in swath along-track/cross-track coordinates. North is approximately to the left. The image on the top shows the large scale view of the storm. Land is shown in dark blue. The bottom image is an expanded view of the eye area. On both images red vectors represent the L2B winds. For the top figure the black vectors are the down sampled SFIC low resolution winds while for the bottom figure the black vectors are the noisy SFIC high resolution winds. Although there exists a cross swath direction bias that is typical of rain contamination, the SFIC method produces a better estimate of the hurricane eye location than the L2B winds for this case.

Simulation methods confirm that this ambiguity selection method performs well in the inner portion of the swath. The SFIC method strongly agrees with NWP winds for wind speeds less than 15 m/s but differs for high winds and hurricane cases, thus validating the new method for the majority of ocean surface wind fields. Furthermore, in some hurricane cases the new method even improves the L2B winds as a nudging field, although heavy rain seems to remain a problem. Various issues, such as rain and land effects will be considered in future research.

REFERENCES

[1] D. G. Long, "High resolution wind retrieval from SeaWinds," *IGARSS*, pp. 751–753, 2002.

[2] B. W. Stiles, B. D. Pollard, and R. S. Dunbar, "Direction interval retreval with threshold nudging: A method for improving the accuracy of QuikSCAT winds," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 40, January 2002.

[3] M. H. Freilich and D. B. Chelton, "Wavenumber spectra of pacific winds measured by the Seasat scatterometer," *Journal of Physical Oceanography*, vol. 16, no. 4, April 1986.

[4] D. W. Draper and D. G. Long, "An advanced ambiguity selection algorithm for SeaWinds," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 41, no. 3, March 2003.

[5] D. G. Long, "Model-based estimation of wind fields over the oceans from wind scatterometer measurements," Ph.D. dissertation, Univerity of Southern California, January 1989.