Evaluation of WindSat Wind Vector Performance With Respect to QuikSCAT Estimates

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***Abstract*—The WindSat instrument was launched on January 6, 2003 as part of a risk reduction effort to assess the potential of using spaceborne fully polarimetric radiometry to measure the marine wind vector. Microwave radiometry on the Special Sensor Microwave/Imager onboard the Defense Meteorological Satellite Program satellites has long provided wind speed measurements. Fully polarimetric radiometry offers the additional possibility of obtaining wind direction as well. By contrast, the QuikSCAT satellite uses active microwave measurements to estimate the wind vector from space. It represents the most comprehensive satellite dataset against which to compare WindSat measurements. In this paper, we systematically compare temporally and spatially coincident WindSat and QuikSCAT wind vector measurements against the design goals of the WindSat instrument, taking into consideration expected differences related to instrument precision and the spatial and temporal variability of the wind field.**

***Index Terms*—QuikSCAT, validation, wind direction, WindSat, wind speed.**

I. Introduction

SINCE the Seasat satellite in 1978, active microwave measurements from space have been used to estimate wind speed and direction [1]–[5]. The fundamental strategy underpinning a scatterometer-based wind vector measurement is straightforward. As the wind blows across the surface, it generates increased surface roughness generally aligned with the wind direction. For moderate incident angles (20° to 60°), the roughness of the ocean surface on the scale of the radar wavelength is responsible for most of the electromagnetic backscatter. The higher the wind speed, the larger the normalized radar cross section (NRCS). The maximum NRCS occurs when the wind is blowing directly into the radar look direction. NRCS is a minimum when the wind direction is perpendicular to the radar look direction. Another slightly smaller, secondary NRCS maximum occurs when the wind blows away from the radar look direction.

For any particular radar incident angle and look direction, geophysical model functions relate wind speed, wind direction, and NRCS. Unfortunately, an inversion to wind speed and direction using only NRCS is not unique. A single NRCS can be associated with many different pairs of wind speed and direction. To circumvent this limitation, scatterometers measure the NRCS at any particular patch on the ocean from different look directions, incident angles, and polarizations. These multiple measurements and considerations of wind field continuity are usually sufficient to retrieve a unique wind vector.

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QuikSCAT's SeaWinds [6] instrument represents the latest implementation of spaceborne microwave wind-measuring scatterometry. The Adeos-2 satellite, launched after QuikSCAT, carried a similar scatterometer, but that satellite was lost in October 2003. The SeaWinds scatterometer uses two rotating, pencil-beam Ku-band (13.4 GHz) radars to measure the NRCS of the surface at two incident angles (46° and 54°), two polarizations, and two angles with respect to the wind. The combination of these measurements is used to estimate the wind vector [7]–[11].

Ocean surface passive microwave emissions also depend on surface roughness. Hence, surface emission is also a function of both wind speed and direction. The wind speed signal in these emissions, i.e., the change in brightness temperature with increasing wind, is much larger than the direction signal, the change in brightness as a function of relative wind direction. Wind speed measurements from microwave radiometry were demonstrated by Seasat's Scanning Multichannel Microwave Radiometer (SMMR) [12]. These radiometric wind speed measurements were sufficiently mature and reliable that they were implemented operationally with the Special Sensor Microwave/Imager (SSM/I) instrument on the Defense Meteorological Satellite Program (DMSP) satellites.

Theoretical work over the last two decades [13], [14], careful analysis of SSM/I data [15]–[17], and aircraft measurements [18] demonstrated that there is also a small, but measurable, wind direction signal in microwave polarimetric emissions from the ocean surface. These developments represent the source of the notion that it might be operationally possible to measure wind vectors from space using passive polarimetric radiometry. The WindSat instrument was launched in 2003 precisely to assess whether such passive polarimetric radiometry from space could actually yield, in addition to wind speed, wind direction measurements.

The Conically scanning Microwave Imager Sounder (CMIS) is a passive microwave instrument, and it is a core instrument of the National Polar-orbiting Operational Environmental Satellite System (NPOESS). The environmental data records (EDRs) CMIS is designed to measure include the vertical profile of atmospheric moisture, cloud ice, liquid water, sea ice, and sea ice edge, as well as sea surface temperature. If the WindSat experiment proves successful in measuring both wind speed and direction to the required accuracy, then CMIS should also be able to produce the ocean surface wind vector EDR [19], and NPOESS satellites will provide marine wind vectors well into the future. This would alleviate the reliance upon active microwave remote sensing of the ocean surface winds. Table I lists the wind speed and direction requirements for CMIS established by the Integrated Program Office (IPO) [20] for 25-km resolution.

TABLE I
WIND SPEED AND DIRECTION MEASUREMENT ACCURACY REQUIREMENTS FOR NPOESS AT 25-km RESOLUTION

Quantity	Performance
Wind Speed	2 m/s or 10% whichever is larger.
Wind Direction	20° for wind speeds greater than 5 m/s and 25° for wind speeds between 3 and 5 m/s.

Since QuikSCAT represents the state-of-the-art in global wind vector measurements, QuikSCAT measurements are an obvious and logical standard against which to assess and evaluate WindSat wind vector retrievals. Here, we systematically compare temporally and spatially coincident WindSat and QuikSCAT wind vector retrievals. We find that the WindSat wind speed retrievals, when compared to analogous QuikSCAT wind speeds, meet the NPOESS accuracy requirement, at least at the 50-km resolution of the currently available dataset. At this point, the WindSat wind direction retrievals have a higher variance than QuikSCAT retrievals. The wind direction retrievals substantially improve for wind speeds greater than 7 m/s and are most accurate in the 7–20-m/s wind speed regime.

II. COMPARISON DATASET

Both the QuikSCAT and WindSat datasets were obtained from the NASA Jet Propulsion Laboratory's Physical Oceanography Distributed Active Archive Center.

A. *Quikscat Wind Vector Retrieval*

For the comparisons considered here, we have used the QuikSCAT level 2B science data. At this earlier processing level, the data are sampled at the resolution of the actual measurements rather than having been rebinned into a regular longitude-latitude grid as with level 3 data. These retrievals have a 25-km resolution.

The QuikSCAT data include not only wind vector retrievals but also measurement times, geographic locations, and geometries, as well as other housekeeping data. There are two sets of wind vector retrievals in the QuikSCAT level 2B product. The first is the QuikSCAT program's nominal wind vector retrieval. This retrieval has a four-fold directional ambiguity, but a selection as to the most likely wind vector is provided.

The selection of the appropriate ambiguity is an additional source of error. One can select the most likely vector on the basis of the difference between the predicted and observed radar cross sections, or also incorporate considerations of wind field continuity. Draper and Long [21] provides a through analysis of ambiguity removal.

The second retrieval uses the DIRTH algorithm [22], which produces only a single wind vector retrieval. This latter retrieval is an experimental one. Here, we rely only on the nominal QuikSCAT wind vector retrievals for our comparisons. These QuikSCAT data also include a number of data quality flags [23].

B. *WindSat Wind Vector Retrieval*

1) Wind Speed: The WindSat EDR data are also comprised of wind vectors, times, geographic locations, measurement geometry, as well as sea surface temperature, water vapor, and rain rate retrievals. The *WindSat Data User's Manual, Version 1.0* [24] explains that the wind speed retrieval for these EDRs is computed using the following equation:

$$u = A_0(\nu) + A_1(\nu)T_{10.7v} + A_2(\nu)T_{10.7h} + A_3(\nu)T_{18.7v} + A_4(\nu)T_{23.8v} + A_5(\nu)T_{37.0v} + A_6(\nu)T_{37.0h} \quad (1)$$

where u is wind speed referenced to 10-m height for neutral atmospheric stability and the $A_i(\nu)$ terms are coefficients dependent upon the water vapor retrieval, ν. The T-values in (1) are the measured brightness temperatures in kelvins, at different frequencies. The subscripts indicate frequency in gigahertiz, at either horizontal (h) or vertical (v) polarization. In addition, there is a modification of each term to account for cross-scan bias in the sensor data records.

It should be noted that these coefficients were tuned by regression with Global Data Assimilation System (GDAS), SSM/I, and QuikSCAT data. Hence, in a sense, though this paper represents a WindSat program-independent assessment of QuikSCAT and WindSat, the creation of the WindSat retrieval algorithm does rely, in significant part, upon QuikSCAT wind vectors. Roughly two-thirds of the six months of WindSat EDR data now available were used in the WindSat training set. We presume here that the dataset is still sufficiently large to draw meaningful comparisons between WindSat and QuikSCAT wind vector retrievals.

2) Wind Direction: From a linear combination of the elements of the full radiometric Stokes vector [25], it is possible to construct the effective field for any polarization. In the context of passive polarimetric measurements, the Stokes vector is often represented by

$$T = \begin{bmatrix} T_v \\ T_h \\ U \\ V \end{bmatrix} = \begin{bmatrix} T_v \\ T_h \\ T_{45} - T_{-45} \\ T_{lhc} - T_{rhc} \end{bmatrix} \quad (2)$$

where the subscripts h, v, -45, 45, lhc, and rhc indicate horizontal, vertical, $-45°$, $45°$, left-hand circular, and right-hand circular polarizations, respectively. There is a weak wind direction signal in the horizontally and vertically polarized emissions [15]. A stronger wind direction signal lies in the U and V Stokes parameters [16], [24].

The WindSat program wind direction retrievals are based upon geophysical model functions for the third and fourth elements of the Stokes vector. These model functions take the form

$$U = \tau^2[U_0(f) + U_1(f)\sin\phi + U_2(f)\sin 2\phi] \quad (3)$$

$$V = \tau^2[V_0(f) + V_1(f)\sin\phi + V_2(f)\sin 2\phi] \quad (4)$$

where τ is atmospheric transmittance, the U_i and V_i are frequency-dependent (f) coefficients, and ϕ represents the angle between the wind direction and radiometer look direction. The geophysical model function used in the retrieval is currently being extended to include terms linear in τ as well.

Using these model functions, a wind speed and direction are selected that minimizes the differences between the modeled Us and Vs at the various frequencies and the observed brightness

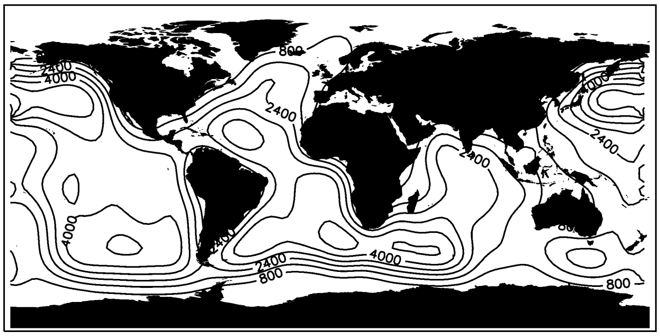

Fig. 1. Contour map of the geographic distribution of QuikSCAT and WindSat match-ups used here. The units are in matchups per square degree of longitude and latitude.

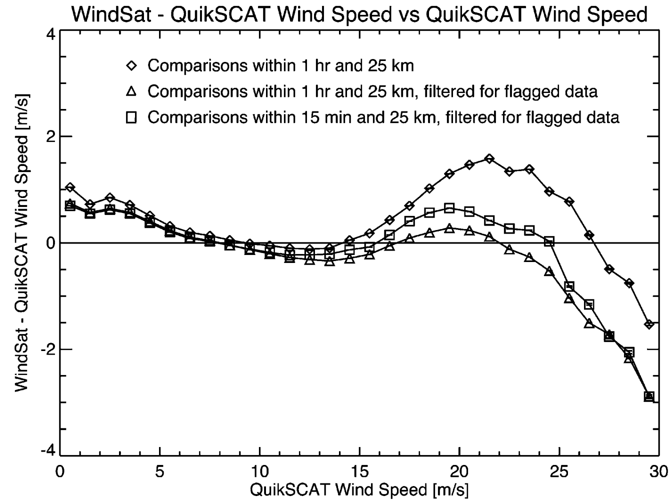

Fig. 2. Difference between WindSat versus QuikSCAT wind speed retrievals as a function of QuikSCAT wind speed for the period September 2003 through February 2004. The diamonds represent comparisons within 1 h and 25 km. The triangles represent comparisons within 1 h, 25 km, and filtered to eliminate rain-contaminated and high water vapor comparisons. The squares represent comparisons within 15 min, 25 km and filtered to eliminate rain-contaminated and high water vapor comparisons.

temperatures. A 7×7 circular median filter is then applied to remove wind direction outliers. The National Center for Environmental Prediction (NCEP) model wind directions at a $1^\circ \times 1^\circ$ longitude–latitude grid are used to help initialize the median filter. Jelenak *et al.* [26], [27] provide a more complete description of the WindSat vector retrievals.

We should note here that the WindSat EDRs are provided at the surface resolution of the 6.8 GHz radiometer, or roughly 50 km. Retrievals at 25-km resolution would undoubtedly be nosier. Additional analysis is required to reassess the performance of WindSat at this higher resolution.

3) Assembly of the Comparison Data: The comparison dataset under consideration here covers the six-month time period September 1, 2003 through February 29, 2004. To assemble a comparison dataset, we read all available WindSat EDRs from the period. Since WindSat data are sampled at 12.5 km though the resolution of the measurement is about 50 km, we subsampled these EDR wind vector estimates by a factor of five. For each remaining WindSat wind vector estimate, we found those QuikSCAT wind vectors that were acquired within 1 h of the WindSat data. Occasionally, there would be two sets of QuikSCAT measurements, one at sometime before the WindSat measurement and one later than the WindSat measurement. We retained the one closest set in time. From this set of measurements, all of which fell within 25 km of the WindSat measurement, we retained the geographically nearest one.

We should note here that WindSat-QuikSCAT comparison match-ups tend to be bunched in areas, both sampling the same synoptic atmospheric conditions. Thus, WindSat and QuikSCAT match-ups are not entirely independent.

The final comparison dataset allows us to evaluate QuikSCAT and WindSat wind speed and direction retrievals under various conditions. For example, we can include or exclude data points potentially contaminated by rain or water vapor or isolate data within specified wind speed regimes.

4) Geographic Distribution: The geographical locations of the WindSat and QuikSCAT comparison pairs are not entirely random, but represent a complex interaction of orbit phasing and swath width. Fig. 1 is a slightly smoothed contour map of WindSat-QuikSCAT data match-up density used here, in units of match-ups per square degree of longitude and latitude. There tend to be more measurements at high latitudes where the polar-orbiting QuikSCAT and WindSat satellites sample more frequently. A more thorough analysis might consider the residual wind vector difference as a function of geographical location as opposed to bundling all the comparisons together. We should note that since GDAS provides global assimilated wind vector estimates, the tuning of the WindSat geophysical model function is not as geographically localized as the WindSat-QuikSCAT match-up distribution shown in Fig. 1.

III. Wind Speed Comparisons

The residual differences between WindSat and QuikSCAT wind speed retrievals are dependent on which comparison pairs we choose to consider. Fig. 2 represent the difference between WindSat and QuikSCAT wind speed retrievals versus QuikSCAT wind speed estimates using difference acceptance criteria. Data are binned in 1-m/s intervals of QuikSCAT wind speeds. There are also error bars on the plot showing the 90% confidence limits, given the number of comparisons within the interval. The sheer number of comparisons is so large that these error bars are smaller than the symbols in the plot.

Since many comparisons might come from the same synoptic weather situation, it is certainly not true that all the comparisons are completely independent. Hence, these error bars represent an upper bound on the statistical reliability of the results. The fluctuation of the points about a smoothed fit might be a better measure of the statistical variability.

The diamonds represent the difference between WindSat and QuikSCAT wind speed retrievals for all comparisons included in this dataset separated by less than 1 h and 25 km The associated mean wind speed difference is 0.22 m/s with a standard deviation of 3.4 m/s.

However, there are a number of situations where we know the wind speed comparisons are invalid. QuikSCAT is known to be affected by rain, while both rain and high levels of atmospheric water vapor can invalidate WindSat retrievals. These contaminated data are flagged in the WindSat and QuikSCAT datasets.

TABLE II

STATISTICS FOR THE DIFFERENCE BETWEEN WINDSAT AND QUIKSCAT WIND SPEED RETRIEVALS. THE SPATIAL DISTANCES BETWEEN MEASUREMENTS ARE LESS THAN 25 km. CASE I: COMPARISONS WITHIN 1 h. CASE II: SAME AS CASE I EXCEPT FILTERED WITH WINDSAT AND QUIKSCAT FLAGS FOR RAIN AND/OR HIGH WATER VAPOR. COMPARISONS WITH WINDSAT WIND SPEED RETRIEVALS GREATER THAN 50 m/s ARE EXCLUDED. CASE III: SAME AS CASE II EXCEPT EXCEPT THE MAXIMUM TIME SEPARATION IS 15 min

Case	Mean	Std.Dev.	N	ρ
I	0.22 m/s	3.43 m/s	11,341,230	0.729
II	0.07 m/s	1.72 m/s	10,994,514	0.894
II	0.09 m/s	1.71 m/s	3,245,111	0.898

In addition, we noted that though most WindSat measurements fell close to QuikSCAT wind speeds, the WindSat retrievals showed a disproportionately large number of very high wind speeds. Such high wind speed estimates could result from unflagged atmospheric contamination. Because of this observation and the fact that no passive wind speed algorithms have been thoroughly validated at these hurricane-level wind speeds [3], [15], we excluded such comparisons where the WindSat speed retrieval was greater than 50 m/s. After removing flagged data[1] and data with WindSat wind speed retrievals higher than 50 m/s, the total number of data comparisons is only reduced by 3.5%, but the mean wind speed difference drops to 0.07 m/s and the standard deviation falls dramatically to 1.72 m/s. These results are plotted in Fig. 2 as triangles.

The closer in time that the WindSat and QuikSCAT retrievals are acquired, the more likely the two measurements are measuring the same wind field. The squares in Fig. 2 represent the difference in WindSat and QuikSCAT wind wind speed retrievals, where we have now retained only those comparison pairs that are separated by less than 15 min. The number of comparisons is reduced by a factor of four, but wind speed comparisons only marginally improve, with a mean difference between QuikSCAT and WindSat of 0.09 m/s and a standard deviation of 1.71 m/s. Table II summarizes the numerical results of these comparisons. In the table, N is the number of comparisons and ρ represents correlation coefficients.

Limiting the spatial separations between QuikSCAT and WindSat comparisons within our data base did not appreciably effect the comparisons. Using a maximum temporal separation of 1 h to keep a large number of potential comparisons, applying the rain and water vapor filtering, and using a 25-km maximum separation the standard deviation between measurements was 1.72 m/s. By keeping only comparisons separated by less than 5 km, the number of comparison dropped from 10 994 514 to 769 986, but the standard deviation dropped only marginally to 1.69 m/s.

IV. WIND DIRECTION COMPARISONS

Comparisons between WindSat and QuikSCAT retrieved wind directions reveal interesting behavior. Fig. 3 represents the difference between the WindSat and QuikSCAT wind direction retrievals as a function of QuikSCAT-estimated wind direction,

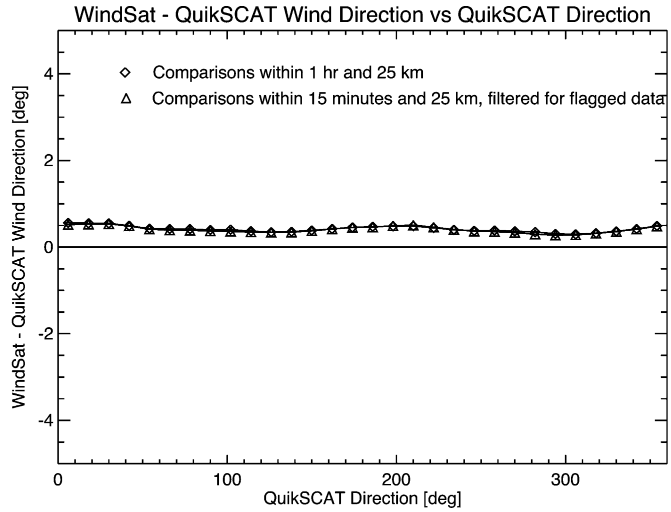

Fig. 3. WindSat minus QuikSCAT wind direction retrievals as a function of QuikSCAT wind direction for the period September 2003 through February 2004. The diamonds represent comparisons within 1 h and 25 km. The triangles represent comparisons within 15 min, 25 km, and filtered to eliminate rain-contaminated and high water vapor comparisons.

TABLE III

STATISTICS FOR THE DIFFERENCE BETWEEN WINDSAT VERSUS QUIKSCAT WIND DIRECTION RETRIEVALS. THE SPATIAL DISTANCES BETWEEN MEASUREMENTS ARE LESS THAN 25 km. CASE I: COMPARISONS WITHIN 1 h. CASE II: COMPARISON ARE WITHIN 15 min, FILTERED WITH WINDSAT AND QUIKSCAT FLAGS FOR RAIN AND/OR HIGH WATER VAPOR. COMPARISONS WITH WINDSAT WIND SPEED RETRIEVALS GREATER THAN 50 m/s ARE EXCLUDED

Case	Mean	Std.Dev.	N	ρ
I	0.09°	29.75°	11,341,230	0.645
II	0.27°	28.39°	3,245,111	0.666

binned in 12° increments. The triangles were computed from the entire comparison database including comparison pairs separated by less than 1 h and 25 km. The bias in wind direction is a small 0.09°. Moreover, the bias between the measurements is not a strong function of wind direction. However, the standard deviation of 29.8° appears quite high given a design goal of 20°. Even if we apply stringent comparison acceptance criteria, the wind direction retrievals do not improve much. The diamonds in Fig. 3 represent the difference between WindSat andQuikSCAT wind directions for measurements separated by less than 15 min and for which rain and high atmospheric liquid water contamination have been excluded. The angular standard deviation is 28.4° See Table III.

It is also clear that the wind direction retrieval accuracy is a strong function of wind speed. This observation is illustrated in Fig. 4. Both curves in the figure were computed for comparisons separated by less than 15 min in time and 25 km in space. The data are also filtered for rain and high water vapor. Data for WindSat wind speeds greater than 50 m/s are excluded. The curve represented by diamonds include only comparisons where the QuikSCAT wind speeds range from 0–3 m/s. The mean angular difference is small, 1.3°, but the standard deviation is a large 54.4°. However, at higher wind speeds, the wind direction retrieval comparisons radically improve. The triangles in Fig. 4 represent comparison data within the 9–10-m/s wind speed range. The mean bias between the WindSat and

[1]The WindSat rain flag is set, i.e., rain is presumed present, when $T_{37v} - 0.979T_{37h} < 55.0°$ or $1.175T_{18v} - 30.0° > T_{37v}$ or $T_{18h} > 170.0°$ or $T_{37h} > 210°$. The cloud liquid water flag is set when the retrieved value of cloud liquid water is > 1.0 mm. The total precipitable water flag is set when the retrieved value of total precipitable water is > 55.0 mm.

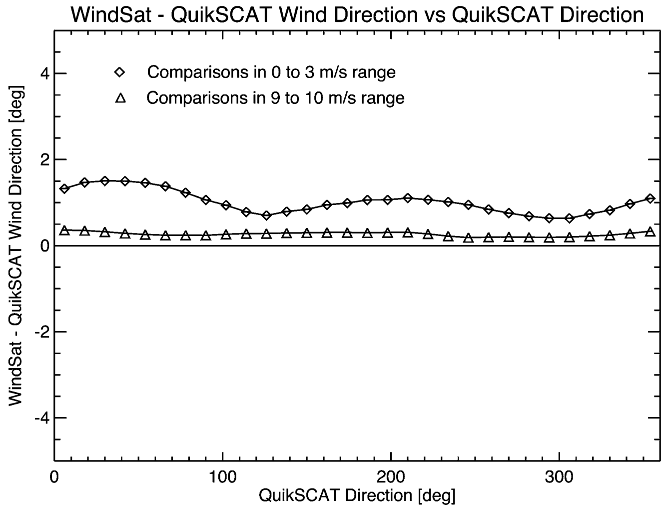

Fig. 4. Difference between WindSat and QuikSCAT wind direction retrievals as a function of QuikSCAT wind direction for the period September 2003 through February 2004. All data comparisons are separated by less than 15 min and 25 km. The diamonds represent only data in the 0–3-m/s wind speed regime. The triangles represent data in the 9–10-m/s wind speed regime.

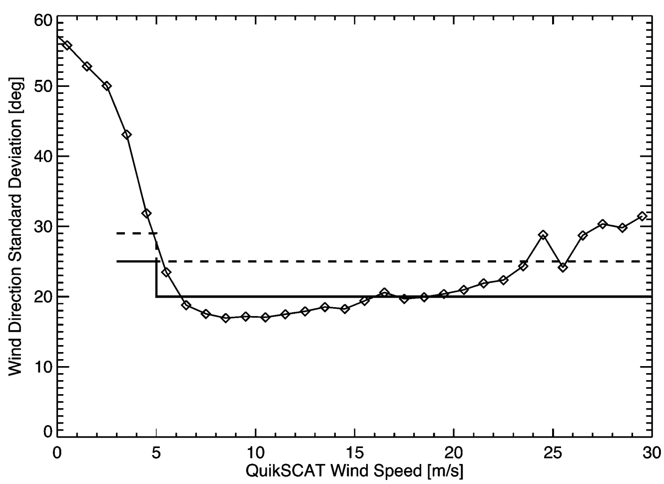

Fig. 5. Standard deviation in the wind direction difference between WindSat and QuikSCAT as a function of QuikSCAT estimated wind speed. The solid line represents that WindSat design goal.

QuikSCAT wind direction retrieval is 0.19°, and the standard deviation is 17.0°.

Fig. 5 is a plot of the standard deviation of the difference between WindSat and QuikSCAT wind direction retrievals as a function of QuikSCAT wind speed. The biases for all these cases are small. Note the rapid decrease in the standard deviation between the WindSat and QuikSCAT wind direction for wind speeds between 0–5 m/s. For wind speeds greater than 7 m/s, the standard deviation levels out in the below 20° range, remaining low until a 20-m/s wind speed when the residuals gradually increase. We note here that wind direction retrievals from QuikSCAT are also poorer at lower wind speeds. We discuss the implications of this below.

V. Evaluation

Whether or not WindSat wind vector retrievals are achieving specified performance levels depends, in significant measure, upon an accurate accounting of various sources of the differences between the WindSat and QuikSCAT retrievals. Monaldo [28]–[30] attempted to enumerate and quantify some these sources of difference. These include not only finite NRCS precision in the QuikSCAT measurements and imperfect knowledge of the associated geophysical model function, but also the temporal and spatial proximity of the QuikSCAT and WindSat measurements. The expected differences for wind speed are listed in Table IV [28], [29].

TABLE IV
Expected Differences in Wind Speed Between WindSat and QuikSCAT

Type	Difference (m/s)
QuikSCAT Instrument	0.89
Temporal Proximity	0.5
Spatial Proximity	0.0
Space Averaging	0.18
Total	1.0

Summed together, even if the WindSat wind speed measurements were perfect, one would still expect to observe about a 1-m/s standard deviation between the WindSat and QuikSCAT wind speed retrievals. The observed standard deviation of 1.71 m/s suggests that the residual WindSat wind speed retrieval errors associated with finite WindSat radiometric accuracy and imperfect knowledge of the associated geophysical model function is

$$\sqrt{(1.71\ \mathrm{m/s})^2 - (1\ \mathrm{m/s})^2} = 1.4\ \mathrm{m/s}.$$

This is well within the 2.0-m/s performance goal. Given the experience with SSM/I radiometric wind speed retrievals, this result was certainly expected. Of course, we should remember that this accuracy assessment applies to 50-km WindSat resolution data.

The results with regard to the wind direction retrievals are less well understood and more difficult to sort through. Freilich and Dunbar [8] found that the random error in the NSCAT scatterometer in wind direction to be 14.4°. Not only might the QuikSCAT performance be marginally different given its different antenna configuration, it is not known how much additional difference in WindSat and QuikSCAT directions would be associated with the space separation between these measurements and spatial averaging. Nor do we know the precise QuikSCAT wind direction retrieval performance as a function of wind speed. Given past experience, one would also expect better scatterometer wind direction retrieval performance for wind speeds greater than 3 m/s [31].

Though the effects of spatial proximity and spatial averaging have not been assessed for wind direction, it is possible, using buoy wind direction data, to estimate the effect of temporal proximity. We acquired National Data Buoy Center (NDBC) data covering the years 1997 through 2000. These data were broken up in 12-h segments of wind direction data sampled every hour. A total of over 770 000 such buoy-based records were used. We then computed the mean autocorrelation function appropriate for angular [32] data for these records. If $\rho_\phi(\tau)$ represents the wind direction autocorrelation function as a function of temporal offset, then the expected difference in wind direction as a function of time, $\phi_d(\tau)$, associated with the temporal

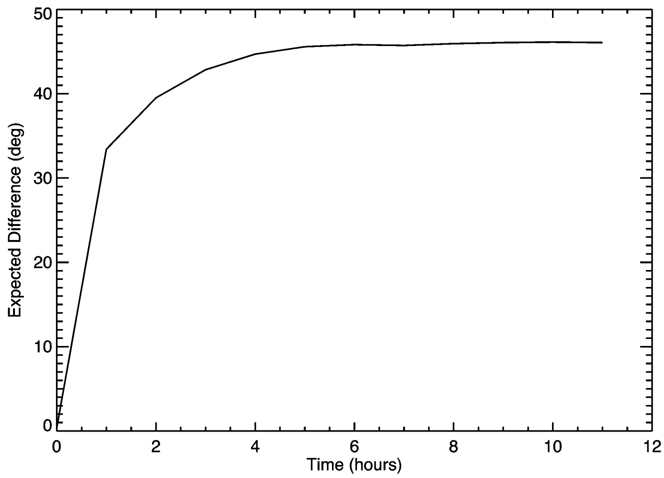

Fig. 6. Expected difference between two wind direction measurements as a function of the temporal separation of the measurements, as estimated from NDBC buoy record.

TABLE V
EXPECTED DIFFERENCES IN WIND DIRECTION BETWEEN WINDSAT AND QUIKSCAT

Type	Difference
QuikSCAT Instrument	14.4°
Temporal Proximity	4.0°
Spatial Proximity	—
Space Averaging	—
Total	15.0°

variability of the wind field is given by $\phi_d(\tau) = \sigma_\phi[2(1 - \rho_\phi)]^{1/2}$, where σ_ϕ is the standard deviation of the angle measurements. This function is plotted in Fig. 6.

Assuming a 15-min maximum separation between QuikSCAT and WindSat measures and a mean separation of 7.5 min, we can interpolate the values in Fig. 6 and estimate an expected difference of 4° associated with temporal proximity. Table V is analogous to Table IV save it applies to wind direction rather than wind speed.

If we assume for the present that the sources that we have not enumerated are negligible, and we need only concern ourselves with the scatterometer random direction error and temporal proximity, and if the WindSat wind direction retrieval error goal is 20°, then the total, observed standard deviation between WindSat and QuikSCAT wind direction retrievals should be

$$\sqrt{(15^\circ)^2 + (20^\circ)^2} = 25^\circ.$$

Hence, very conservatively, we can aver that if the observed QuikSCAT-WindSat comparison differences are less than 25° then the WindSat contribution to these errors is less than 20°. Fig. 5 suggests that within the 7–25-m/s wind speed regime, WindSat direction errors are certainly less than 20°. At lower wind speeds, the issue becomes far more uncertain.

Note that the IPO wind vector direction requirement relaxes to 25° in the 3–5-m/s wind speed regime. Thus, differences with respect to scatterometry could be as large as 29° for wind speed between 3–5 m/s and still be meeting the performance requirements in the lower wind speed regime.

Fig. 5 illustrates these points. The solid line represents the nominal wind direction retrieval goals of WindSat. The dashed line represents the wind direction retrieval cutoff after taking into account other sources of wind direction difference between WindSat and QuikSCAT. Thus, whereever the observed wind direction standard deviation falls below the dashed line, WindSat is meeting its design goals.

A number of points modulate the results and tend to make these WindSat-QuikSCAT direction comparisons an upper bound on the WindSat wind direction retrieval errors.

First, QuikSCAT comparisons are degraded in the far swath where the ocean surface is sampled by only the largest incident angle antenna, as well as near the satellite ground track where the measurement geometry is not optimal. Citations of QuikSCAT performance are usually given excluding these problem areas. However, here we have considered all QuikSCAT data regardless of where in the swath the measurement was acquired. As a consequence, the contribution to the total WindSat-QuikSCAT wind direction residuals from random QuikSCAT errors could be larger than 14.4°.

Second, comparisons with buoy data suggest that wind direction retrievals from QuikSCAT are also strongly dependent on wind speed. Ebuchi [31] demonstrated for all wind speeds the standard deviation of the direction differences was 27.8°. The residual differences dropped to 20.6° for all wind speeds greater than 3 m/s and fell to 16.2° for wind speeds greater than 5 m/s. Hence, the WindSat-QuikSCAT direction differences should dramatically increase at low wind speeds just because of documented QuikSCAT differences with respect to buoy measurements at the low wind speeds.

Given the above issues, it is quite possible that WindSat is meeting its design goals with respect to direction despite the observed differences with QuikSCAT retrievals. More attention needs to be devoted to an error analysis of direction retrievals in the lower wind speed range before more definitive conclusions may be legitimately drawn.

We note here another small issue which has not yet been sufficiently explained. Jelenak *et al.* [26], [27] showed that both WindSat and QuikSCAT wind direction retrievals, compared independently with GDAS wind direction estimates, decrease with wind speed as estimated from GDAS. We find here that the standard deviation in direction measurements between WindSat and QuikSCAT as a function of QuikSCAT-estimated wind speed also decreases dramatically with increasing wind speed. However, as shown in Fig. 5, at wind speeds near 20 m/s the residuals begin to increase. Jelenak *et al.* [26], [27] use GDAS wind speed to bin the data. Here we used QuikSCAT-estimated wind speed.

VI. CONCLUSION

The measurement of wind direction with microwave polarimetric radiometry from space is still in its earliest stages. We anticipate additional improvements in wind direction retrievals as atmospheric attenuation corrections are improved and as the understanding of geophysical model function grows.

At this point, we conclude that WindSat can meet the NPOESS performance requirements for wind speed accuracy across the entire wind speed range at 50-km resolution. A similar evaluation needs to be made for WindSat data at 25-km resolution.

For wind direction, comparisons with QuikSCAT-derived directions imply that the 20° performance goal is met for wind speeds above 7 m/s. Below this wind speed threshold, the results are not yet clear. The requirement for wind direction performance relaxes to 25° in the 3–5-m/s wind speed regime, suggesting that differences with QuikSCAT as large as 29° would still be consistent with the IPO wind direction performance specification. Moreover the QuikSCAT variance in estimated wind direction with respect to buoy wind direction measurements also increases at lower wind speeds. This would mean that the limit at which WindSat and QuikSCAT wind directions could differ and still imply that WindSat is measuring wind direction to within 25° in the lower wind speed regime would increase. This low wind speed behavior is an important area for future consideration. As with wind speed, these wind direction comparisons need to be reassessed at 25-km resolution as more data become available.

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