An Ocean Surface Wind Vector Model Function for a Spaceborne Microwave Radiometer

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Abstract—Surface wind vector measurements over the oceans are vital for scientists and forecasters to understand the Earth’s global weather and climate. In the last two decades operational measurements of global ocean wind speeds were obtained from passive microwave radiometers (SSM/I’s); and over this period, full ocean surface wind vector data were obtained from several NASA and ESA scatterometry missions. However, since SeaSat-A in 1978, there have not been other combined active and passive wind measurements on the same satellite until the launch of JAXA’s Advanced Earth Observing Satellite (ADEOS-II) in 2002. This mission provided a unique data set of coincident measurements between the SeaWinds scatterometer and the Advanced Microwave Scanning Radiometer (AMSR).

The AMSR instrument measured linearly polarized brightness temperatures ($T_B$) over the ocean. Although these measurements contained wind direction information, the overlying atmospheric influence obscured this signal and made wind direction retrievals not feasible. However, for radiometer channels between 10 and 37 GHz, a certain linear combination of vertical and horizontal brightness temperatures causes the atmospheric dependence to cancel and surface parameters such as wind speed and direction and sea surface temperature to dominate the resulting signal. In this paper, an empirical relationship between AMSR $T_B$’s (specifically $A - T_{Bv} - T_{Bh}$) and surface wind vectors (inferred from SeaWinds’ retrievals) is established for three microwave frequencies: 10, 18 and 37 GHz. This newly developed wind vector model function for microwave radiometers can serve as a basis for wind vector retrievals either separately or in combination with active scatterometer measurements.

Index Terms—Active and Passive Microwave, Ocean Surface Wind Vector, Microwave Radiometry, Scatterometry.

I. INTRODUCTION

Oceanic surface wind vector data provides essential environmental information for scientific and operational applications; and as a result, the demand for these measurements from space continually increases. The advent of the first spaceborne wind scatterometers, on NASA’s SeaSat-A mission in 1978, proved that the global ocean surface wind vector (speed and direction) retrievals from space are possible [1, 2]. This mission was followed by a series of satellite scatterometers that started with the European Remote Sensing Satellite (ERS-1) active microwave instrument in 1991 [3, 4]. Regardless, there have never been sufficient numbers of instruments operating simultaneously to fulfill either the temporal or spatial sampling requirements for scientific applications or operational weather forecasting. Unfortunately, current plans for future satellite ocean surface vector wind measurements do not include scatterometers within next decade.

Most operational meteorological satellites carry passive microwave radiometers such as the series of Special Sensor Microwave Imagers (SSM/I) on-board the Defense Meteorological Satellite Program (DMSP) satellites, which are capable of accurately measuring oceanic surface wind speed but not the wind direction. However, a proof of concept has been demonstrated with the launch of the first fully polarimetric microwave radiometer (WindSat) that was developed by the U.S. Naval Research Laboratory in January 2003. The WindSat instrument is capable of providing full oceanic wind vector measurements [5].

Moreover, since a microwave radiometer also provides other valuable oceanic and atmospheric geophysical information such as sea surface temperature (SST), water vapor, cloud liquid water, and rain rate, it would be highly beneficial to combine active and passive microwave technologies to obtain improved observation of both the ocean surface and the atmosphere.

A. ADEOS-II Mission

The Advanced Earth Observing Satellite (ADEOS-II) was launched on December 14, 2002 by the Japan Aerospace Exploration Agency (JAXA). ADEOS-II carried five earth observing sensors, including the Advanced Microwave Scanning Radiometer (AMSR) and the SeaWinds scatterometer. This was the first satellite mission (since SeaSat-A) that carried both a microwave scatterometer and a radiometer and that provided an opportunity of combining passive and active measurement techniques for inferring ocean surface wind vectors. Even though the ADEOS-II operation was terminated prematurely on October 25, 2003, sufficient

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data were collected to allow for evaluation of this exciting new remote sensing technique.

B. AMSR Description

The AMSR was a microwave radiometer that acquired measurements at eight discrete frequency bands between 6.9 GHz and 89 GHz [6]. Unlike the fully polarimetric radiometer, WindSat, the AMSR only observed the two principle polarizations (vertical and horizontal) from six frequency channels. Although the vertical and horizontal brightness temperatures depend on wind velocity, the contribution of the direction to overall brightness temperature is weak, especially for low wind speeds, and easily obscured by the strong contribution from other atmospheric parameters, such as cloud liquid water and water vapor for higher frequencies, and sea surface temperature, for lower frequencies. Thus, present AMSR ocean geophysical algorithms do not retrieve wind direction. However, previous investigations discovered that a linear combination between the vertical and horizontal brightness temperatures contained relatively robust wind directional signals [7, 8]. These brightness temperature combinations are mostly independent of the atmosphere and are predominantly a function of sea surface temperature (SST), wind speed and wind direction. The linear combination may be written as $A \cdot TBV - TBH$, where $A$ is a constant dependent on the frequency channel used [8].

The stronger sensitivity of this radiometric combination on wind direction provides a potential technique for microwave radiometer wind vector retrieval in the moderate to high wind speed regime; however for low wind speeds, the wind direction signals have poor signal to noise ratio compared to the geophysical retrieval noise level. Therefore, full wind vector retrievals from only passive microwave measurements, using V- and H-pol measurements alone or their linear combination, are not possible for all wind speed regimes.

C. SeaWinds Description

The SeaWinds was a Ku-band (13.4 GHz) scatterometer, which used a mechanically spinning two-beam parabolic reflector antenna to acquire ocean measurements over a full 360° in azimuth. To retrieve ocean surface wind vector, the SeaWinds obtained measurements at vertical and horizontal polarization over a wide-swath (1800 km) that was subdivided into 25 km “wind vector cells” (WVC). As the satellite passed over a given WVC location, the radar backscatter ($\sigma_0$) was collected and averaged at four azimuthal-look directions (i.e., pointing forward and aft at two different incidence angles). These four $\sigma_0$'s were collocated within WVC’s and used in the geophysical algorithm to infer neutral stability wind vector at 10 m height.

For this paper, scatterometer derived ocean surface wind vector data were used as independent “surface truth” to develop the passive $A \cdot TBV - TBH$ geophysical model function (GMF). Section II discusses collocation data set containing AMSR, SeaWinds and a numerical weather model data. The derivation of the $A$ parameter and the characteristics of $A \cdot TBV - TBH$ are described in Section III. Also, the procedure for the model function development and the model function coefficients are presented in Section IV. Finally, an algorithm using forward-looking-only $\sigma_0$ measurements with $A \cdot TBV - TBH$ was investigated to demonstrate the potential of this active/passive technique for measuring wind direction. Algorithm is presented in Section V, Results and validation analyses are presented in Section VI and final conclusions and recommendations are presented in Section VII.

II. MATCH-UP DATASET

It is always important to use the best available dataset to develop a model function from remotely sensed measurements. For ADEOS-II, the AMSR provided the dual polarized radiometric brightness temperatures and the SeaWinds provided simultaneous collocated ocean surface wind speeds and wind directions. The only external data required for “match-up” was the sea surface temperature (SST) provided by NCEP’s Global Data Assimilation Model (GDAS) database. These are the data sources used to develop the $A \cdot TBV - TBH$ model.

AMSR data between April 10 and October 24, 2003 were available to the SeaWinds’ science community. This AMSR overlay level 2A product contained 12 channels of dual polarization brightness temperatures along with the retrieved atmospheric and ocean surface parameters, including water vapor, cloud liquid water, sea surface temperature and sea surface wind speed. These data were formatted into wind vector cell quadrants corresponding to the SeaWinds wind vector format of the L2B product. The vertical (V) and horizontal (H) polarization brightness temperatures for 10.7, 18.7 and 36.5 GHz were used from these AMSR overlay data.

The corresponding SeaWinds science data products, including L2A ocean surface backscatter ($\sigma_0$) and L2B retrieved wind vectors, were gridded on a 25 km spacecraft grid to form WVC’s located symmetrically about the ADEOS-II satellite subtrack. The data file format comprised 76 WVC’s across-track and 1624 rows along-track for each orbit. This structure was similar to that of the AMSR overlay product, except that each WVC was further subdivided into quadrants.

The only external data required for match-up with the AMSR and SeaWinds was the SST product. Although the SST was also retrieved from the AMSR, its accuracy was considered inferior to that provided by the NOAA National Centers for Environmental Prediction’s (NCEP) Global Data Assimilation System (GDAS). The GDAS is a global numerical model of the Earth’s atmosphere and ocean surface, which assimilates a variety of measurements collected from buoys, ships, planes, radiosondes, weather radars, and satellites. Products are generated every 6 hours at 00Z, 06Z, 12Z and 18Z daily on a $1^\circ \times 1^\circ$ global latitude/longitude grid for a limited selection of parameters significant for a satellite geophysical retrievals validation [9]. In addition to SST, GDAS contains other environmental parameters including ocean surface wind speed and direction, and atmospheric
profiles of temperature, moisture and pressure.

For each rev of AMSR data, corresponding GDAS parameters were collocated in WVC quadrants. This collocation process was accomplished using the closest GDAS files within ±3 hr of ADEOS-II orbit time [9]. For each WVC quadrant, the closest four GDAS grid points were spatially interpolated to that WVC location.

The data were separated into two independent datasets: one for training and another for testing. Every three consecutive revs were used for the training set and every fourth was used for the testing set. The training data were prepared for model development by first sorting in 1.0 m/s bins using the retrieved wind speeds from the SeaWinds L2B. Since all of the parameters were stored in the same structure, it conveniently provided corresponding environmental parameters in each wind speed bin. Next the data were further subdivided into 2 C SST bins based on the collocated GDAS product. Finally, the data were subdivided into 10° relative wind direction bins using the wind direction solution from the SeaWinds L2B and the calculated AMSR azimuth direction. The data-binning scheme is illustrated in Fig. 1. The identical binning scheme was repeated for the testing dataset.

Fig. 1. AMSR/SeaWinds/GDAS dataset sorting by wind speed, SST, and the relative wind direction.

III. AV-H

Microwave radiometers measure naturally occurring blackbody microwave emission, and both oceanic and atmospheric geophysical parameters contribute to the total apparent brightness temperatures measured over the ocean. For high microwave frequencies (> 50 GHz), the dominant brightness temperature signal contribution comes from the atmosphere. For lower microwave frequencies (< 37 GHz), the surface emission is strong enough to enable wind speed retrievals using the V or H polarized microwave observations but the wind direction dependent emission is very weak. So weak that accurate knowledge of the atmospheric variables is critical, if a single polarization is going to be used for full wind vector retrieval. Small errors in atmospheric corrections will result in significant errors in wind direction retrievals.

With the linear combination of V and H polarized $T_B$’s, atmospheric corrections may not be required. This linear combination was previously found to be mostly independent of the atmospheric parameters and is predominantly a function of the surface wind speed, wind direction and sea surface temperature (SST) [7, 8]. This brightness temperature combination is expressed as $A \cdot T_{BV} - T_{BH}$ or simply $AV-H$, where $A$ is a constant dependent on microwave frequency [8], as discussed below.

From radiative transfer theory, the total apparent brightness temperature collected at the radiometer antenna may be expressed as

$$T_B = T_{BU} + \tau \cdot e T_S + \tau \cdot r(1 + \Omega)(T_{BD} + \tau \cdot T_C) \quad (1)$$

The upwelling $T_{BU}$ and downwelling $T_{BD}$ atmospheric brightness temperatures, respectively, are given by

$$T_{BU} = \int_0^\infty \alpha(z)T(z)r(z,S)dz \quad (2)$$

$$T_{BD} = \int_0^\infty \alpha(z)T(z)r(0,z)dz$$

The $\alpha(z)$ and $T(z)$ are the atmospheric absorption and physical temperature profiles at altitude $z$, respectively. The total atmospheric transmittance between sea level and the top of the atmosphere, $\tau$ is defined as

$$\tau = \exp\left(-\int_0^\infty \alpha(z)dz\right) \quad (3)$$

The emissivity $e$ and the reflectivity $r$ are related by Kirchhoff’s Law as $r = 1 - e$. The quantity $\Omega$ is the relative surface scattering reflection factor due to a wind roughened surface. The temperature, $T_C$ is the cosmic brightness temperature equal to 2.7 K and $T_S$ is the SST in Kelvin.

Assuming a homogeneous single-layer, the atmosphere may be parameterized in terms of upwelling and downwelling $T_B$’s and the effective air temperatures as

$$T_U = \frac{T_{BU}}{1 - \tau} \quad (4a)$$

$$T_D = \frac{T_{BD}}{1 - \tau} \quad (4b)$$

These effective temperatures are approximately the air temperature averaged over the lower to mid troposphere and are very nearly equal, given the absence of significant rain. Thus, the atmospheric effective temperature is defined as $T_{eff} \equiv T_U \equiv T_D$ and after substituting (4) into (1), becomes

$$T_B \approx (1 - r \cdot \tau^2)T_{eff} + r \cdot \Omega T_{eff} + (1 + \Omega) \cdot r \cdot \tau^2 T_C \quad (5)$$

Since the last two terms in (5) contribute only about 2% of the total, they are ignored and the expression reduces to

$$T_B \approx (1 - r \cdot \tau^2)T_{eff} + \tau \cdot \Delta(1 - r) \quad (6)$$

where $\Delta = T_S - T_{eff}$.

Therefore, from (6) the total brightness temperature is a function of surface reflectivity, the atmospheric transmittance and effective temperature, and the SST. Let $A$ be defined as the ratio between the V and H surface reflectivity.
and using the simplified approximation given in (6), the brightness temperatures can be rewritten in terms of $R_f$ as

$$T_{BV} \approx (1 - R_f \tau^2)T_{eff} + \tau \cdot \Delta(1 - R_f)$$  \hspace{1cm} (8a)$$

$$T_{BH} \approx (1 - AR_f \tau^2)T_{eff} + \tau \cdot \Delta(1 - AR_f)$$  \hspace{1cm} (8b)$$

When we multiply (8a) by $A$ and subtract (8b), the combined brightness temperatures become

$$AT_{BV} - T_{BH} \approx (A - 1)T_{eff} + \tau \cdot \Delta(A - 1)$$  \hspace{1cm} (9)$$

From (7), the $A$ depends on the surface reflectivity at the time of observation, which is not generally known. However from (9), the $A$ may be derived as

$$A \approx \frac{T_{BH} - T_{eff} - \tau \cdot \Delta}{T_{BV} - T_{eff} - \tau \cdot \Delta}$$  \hspace{1cm} (10)$$

For AMSR frequencies of interest, the atmospheric transmission is usually $\tau > 0.7$, and the sea surface temperature is known a priori (or retrieved from the microwave observations); therefore the $A$ reduces to

$$A \approx \frac{T_{BH} - T_s}{T_{BV} - T_s}$$  \hspace{1cm} (11)$$

and from (9), the combined brightness temperature reduces to

$$AT_{BV} - T_{BH} \approx (A - 1)T_s$$  \hspace{1cm} (12)$$

When taking a partial derivative of (12) with respect to $\tau$, this brightness temperature combination becomes

$$\frac{\partial (AT_{BV} - T_{BH})}{\partial \tau} \approx 0$$  \hspace{1cm} (13)$$

This simple linear polarization brightness temperature combination of $AT_{BV} - T_{BH}$ is approximately independent of the atmospheric transmittance, which means that this combination of brightness temperature measurements is almost independent of atmospheric variables such as water vapor and low cloud liquid water (< 0.1 mm). Fig 2. shows the mean of $AV$-$H$ linear combinations for three AMSR frequencies (10 GHz – blue, 18 GHz – red, 37 GHz – green) as a function of water vapor. The mean brightness temperatures were obtained by averaging over entire SST’s, wind speed and direction space. The effectiveness of this $AV$-$H$ linear combination to remove the influence of the atmosphere is apparent for two lower frequency channels (10 and 18 GHz). Large change in the 37 GHz channel combination for low water vapor levels can be attributed to its sensitivity to other surface parameters and atmospheric parameters.
Fig. 3. The $A$ parameter wind speed dependence for 10, 18 & 37 GHz and SST of 19°C. The symbols are means and the bar denotes the standard deviation for each wind speed bin.

Fig. 4. The 10 GHz $A$ parameter wind speed signature, where the colorbar represents SST bins of 4°C steps.

Fig. 5. The 18 GHz $A$ parameter wind speed signature, where the colorbar represents SST bins of 4°C steps.

Fig. 6. The 37 GHz $A$ parameter wind speed signature, where the colorbar represents SST bins of 4°C steps.

Given these $A$ values and the corresponding V and H $T_B$’s, average $AV$-$H$ (over all wind directions) was calculated as a function of wind speed and SST, and results are shown in Figs. 7–9. As observed in these figures, $AV$-$H$ relationships are monotonic and decreasing with wind speed except for the highest three SST bins, at wind speeds > 15 m/s. For the 10 GHz channel at a constant wind speed bin, $AV$-$H$ first decreases with SST until 7°C and then increases for higher SST. On the other hand, for 18 and 37 GHz, the SST dependence at constant wind speed is monotonically decreasing. These curves, for fixed SST, are nearly parallel for most of the SST bins, which allows us to model the $AV$-$H$ as

$$AT_BV - T_BH = F(WSPD) + F(SST)$$

Fig. 7. The 10 GHz $AV$-$H$ wind speed signatures for various 4°C SST bins.
When the wind speed is zero, the surface is assumed to be smooth, and the AV-H in (14) is a function of only SST. The initial $F_{(SST)}$ was estimated by extrapolating the above AV-H signatures to zero wind speed, and the results are shown in Fig. 10.

If the AV-H curves for fixed SST (Figs. 7 – 9) were perfectly parallel, then these curves would collapse to a single curve after subtracting $F_{(SST)}$ from (14); however, this is not the case, as shown in Figs. 11 – 13. As a result, the $F_{(WSPD)}$ function (shown as the square symbols) is set equal to the average values over all SST. It should be noted that this might be the result of the approximations used in the derivation of $A$ given in (11). A fine-tuning adjustment is made later for a DC offset for wind speed.
Based upon the above, the AV-H was found to be the sum of two independent functions of wind speed and SST respectively from $F(WSPD)$ and $F(SST)$. In addition, the sea surface reflectivity exhibited anisotropic behavior with respect to wind direction; and the AV-H combinations calculated above are simply the isotropic DC terms (averaged over all wind directions). Thus, the azimuthal dependence was modeled using a two-term Fourier cosine series, which has been traditionally used by the scatterometer geophysical model function [10], and the AV-H becomes

$$AT_{AV} - T_{AV} = \frac{F(WSPD)}{DC} + F(SST) + C_1(WSPD) \cdot \cos(\chi) + C_2(WSPD) \cdot \cos(2\chi) \quad (15)$$

The relative wind direction ($\chi$) is defined as the difference between the observed azimuth “look” angle and the surface wind direction, using the meteorological wind direction convention. The azimuth look used here was the AMSR scan azimuth relative to North and the wind direction was obtained from the collocated SeaWinds retrieved direction. The relative wind direction, illustrated in Fig. 14, may be expressed as

$$\chi = \text{Azimuth} - \text{WDIR} \quad (16)$$

The wind direction dependence of AV-H is calculated by subtracting the $F(SST)$ & $F(WSPD)$ from the overall AV-H measurement and this defines the wind direction dependence term as

$$F(WDIR) = C_1(WSPD) \cdot \cos(\chi) + C_2(WSPD) \cdot \cos(2\chi) \quad (17)$$

The $F(WDIR)$ is a function of the wind speed as well as the relative wind direction, and it was determined empirically for constant wind speed and the relative wind direction binned every 10°. The $F(WDIR)$ results for 7 m/s at 10, 18 & 37 GHz are shown in Fig. 15. It should be noted that the average of $F(WDIR)$ over all wind directions should equal to zero as predicted in (17); however, a small bias error is caused by estimating $F(WSPD)$ by taking the mean overall SST as shown in Figs. 11 – 13. To eliminate this DC offset error, the directional dependence $F(WDIR)$ was modified as

$$F(WDIR) = C_0(WSPD) + C_1(WSPD) \cdot \cos(\chi) + C_2(WSPD) \cdot \cos(2\chi) \quad (18)$$

where the new term, $C_0$, is equivalent to $F(WSPD)$ as described above, and empirically determined as described below.
IV. MODEL FUNCTION

In this section, the procedure used to obtain the passive model function coefficients is described. The model function was found by using a proper mathematical function to regress the averaged AV-H measurements as a function of the appropriate parameters. From (15), the AV-H model may be rewritten in the form

\[ AV - H = F(SST) + C_0(WSPD) + C_1(WSPD) \cdot \cos(\chi) + C_2(WSPD) \cdot \cos(2\chi) \]  

The initial \( F(SST) \) was found as shown in Fig. 10 by assuming a specular reflection (WSPD = 0). This initial \( F(SST) \) was the average of the AV-H measurements in 2 SST bins based on the GDAS modeled SST. A regression analysis was performed to model the SST dependence, and the resulting best fit for these initial \( F(SST) \) measurements was found for AMSR 10, 18 and 37 GHz channels. Note that the \( F(SST) \), given in Table 1, is a function of SST in Kelvin.

Next, using this function and subtracting from the individual measurement of AV-H, the resulting wind vector dependence term is modeled as

\[ (AV - H) - \left[ C_0(WSPD) + C_1(WSPD) \cdot \cos(\chi) + C_2(WSPD) \cdot \cos(2\chi) \right] = F(SST) \]  

The procedure was repeated to find the proper mathematical form that best fit the mean values for each SST bin and the new coefficients for \( F(SST) \) were found. The new GMF coefficients were found by repeating this process with newly evaluated \( F(SST) \) subtracted from the AV-H measurements.

After several iterations, the final functional form for \( F(SST) \) and the GMF \( "C" \) coefficients converged and remained the same. The GMF after the last iteration represents the empirical model for AV-H brightness temperature as a function of SST and vector wind as defined in (19). The empirical model equations and model coefficients are presented in Table 1 and Table 2 respectively.
Using the functional forms and corresponding coefficients from Table 1 and Table 2 for three AMSR frequency channels, the model function is plotted for each component of the model: \( F(\text{SST}) \), \( C_0 \), \( C_1 \) and \( C_2 \) as shown in Figs. 16 – 19 respectively. The symbols represent the mean value of the measurements and the solid lines are the modeled functions. From these \( C \) coefficients, the wind vector anisotropy is plotted with the DC term, \( C_0 \) removed in Figs. 20 – 22 for 10, 18 and 37 GHz respectively for selected wind speed ranges.
V. WIND VECTOR RETRIEVAL

A. Wind Vector Retrievals from Passive Microwave Measurements

The major application of the $A_V$-$H$ model function developed in Section IV is wind vector retrieval. Since the model function depends on both wind speed and direction, ultimately both of these parameters can be retrieved from these measurements. Further, improvements should be possible in other surface and atmospheric parameters because of the removal of the wind direction bias present in current passive microwave retrieval algorithms.

Referring to Figs. 20 – 22, for low to moderate wind speeds ($< 9 \text{ m/s}$), the $T_B$ anisotropy is weak compared to expected geophysical retrieval noise level, and this makes it difficult to use passive microwave measurements alone for wind direction retrieval. However, for stronger winds, the anisotropy signal to geophysical noise ratio is improved and good wind direction retrievals are possible.

An example of the $A_V$-$H$ model function (shown in solid red line) compared to $A_V$-$H$ from independent measurements (withheld testing dataset) is illustrated in Fig. 23 for 18 GHz and a wind speed of 15 m/s. The scatter of $A_V$-$H$ points about the model function, herein called geophysical noise, represents the modeling error caused by other geophysical parameters (e.g., SST, water vapor and cloud liquid water). Also apparent in the figure is an asymmetry in the $A_V$-$H$ model function, especially between 270° - 360°, which is the result of the assumed even function (cosine harmonics) anisotropy model and the fact that the model was trained using relative wind directions between 0° - 180° (rather than 0° - 360°). An improved training procedure could remove some of these systematic differences, but the standard deviation of the geophysical noise is not expected to improve. Nevertheless, this example results in a wind direction anisotropy signal to noise ratio of ~ 4, which is adequate for good wind direction retrievals.
In order to perform maximum likelihood estimation (MLE) wind direction retrievals, knowledge of the measurement error variance is very important, and this was empirically determined for all wind speed and relative wind directions. An example of the geophysical noise standard deviation as a function of relative wind direction for 15 m/s is given in Fig. 24. The variance of this error was modeled in the same manner as the empirical model function of $A\nu$-H measurements in (18).

On the other-hand, microwave scatterometer model functions have strong wind direction anisotropy that allows accurate wind vector retrievals over practically all ocean wind speeds. The difficulty of the scatterometer wind measurement technique is that it requires a WVC to be observed from multiple azimuth directions (both forward and aft viewing). This 360° azimuth viewing geometry causes difficulties in instrument accommodations on most remote sensing spacecraft; however, a single azimuth-look scatterometer (i.e., either forward or aft) would be a more favorable configuration from a satellite instrument accommodation standpoint. Further, the integration of a single-look scatterometer with a conical scanning radiometer could retrieve wind vector over all wind speeds with significant reduction in complexity and hardware cost over two stand-alone instruments.

To test the hypothesis that active/passive wind vector measurements are possible, we combined the passive AMSR measurements with active SeaWinds measurements on the ADEOS-II. Using this favorable combination of simultaneous active fore-look $\sigma_0$’s and passive $A\nu$-H brightness, we present wind direction measurements in the next section, which demonstrated that this wind vector measurement technique is feasible.

In this paper, our focus is only on the novel active/passive wind direction retrieval because wind speed remote sensing is routinely provided. In order to assess the feasibility, we use the MLE approach of minimizing an objective function of the combined measurements given by (22) with the assumption that wind speed and sea surface temperature are known a priori. The first summation represents the normalized residual of the $A\nu$-H brightness temperature between measured and the modeled signal, where the squared-residual is normalized by the model function variance calculated previously. The second summation represents the residual between the measured $\sigma_0$ and the scatterometer GMF, where the squared-residual was normalized by their corresponding variance. Given the wind speed, SST and the active/passive measurements, the wind direction solutions are found by searching for the directions that correspond to the local minima of the objective function. Due to the biharmonic nature of the model functions, there were multiple wind direction solutions or ambiguities (aliases) found. These direction ambiguities were ranked according to the inverse values of the objective function, i.e., the 1st ranked (most likely) solution is the direction that resulted in the lowest minimum value in (22). The multiple solutions (up to four) were kept.

\[
\zeta = \sum_{\text{freq}=10,18,37\text{GHz}} \left( \frac{A\nu\text{H}_{\text{meas}} - A\nu\text{H}_{\text{model}}(\text{wspd, rel dir, SST})_{\text{freq}}}{\text{Variance}_{A\nu\text{H}}(\text{wspd, rel dir})_{\text{freq}}} \right)^2 + \sum_{\text{pol}=V,H} \left( \frac{\sigma_0 - \text{GMF}(\text{wspd, rel dir})_{\text{pol}}}{\text{Variance}_{\sigma_0}(\text{wspd, rel dir})_{\text{pol}}} \right)^2 \tag{22}
\]
VI. RESULTS

A. Wind Direction Accuracy

Using the testing dataset, the combined active/passive wind direction retrievals were evaluated, and for comparison purposes we used an independent set of wind directions from the GDAS as surface truth. There were up to four possible wind direction solutions, and the one closest to the GDAS wind direction was selected. Although, this produced optimistic results (i.e., perfect ambiguity selection), the corresponding selected solution ranking was recorded and the retrieval skill was evaluated (see Sec.B below). Wind direction error statistics for selected wind speed bins are given in Table III. Also shown are the comparisons between GDAS and the SeaWinds L2B selected wind directions. The active/passive wind direction retrieval errors, in the various wind speed bins, are all acceptable compared to the direction measurement requirement of \( \pm 20^\circ \). Although they are significantly larger than the SeaWinds four-look scatterometer retrievals, considering the preliminary nature of this active/passive retrieval algorithm, these results are encouraging.

<table>
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<th>Wind Speed (meter/sec)</th>
<th>Number of Points</th>
<th>Standard Deviation Error (GDAS retrieval)</th>
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<td>Passive</td>
<td>Passive (exclude 37 GHz)</td>
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<td>(e.g., SeaWinds)</td>
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</table>

B. Ambiguity Selection Skill

The active/passive ambiguity selection skill was evaluated using the ranking of the closest wind direction to GDAS, and the results are shown in Table IV. For higher wind speeds, the combined 1st & 2nd ranked ambiguities were closest to the GDAS wind direction in approximately 80 – 90% of cases, which implies relatively high retrieval skill. However, for low to moderate wind speed, the skill for the first two ranked ambiguities was lower and the probability of the 3rd ranked solutions being the correct solution increased. Nevertheless, this result is similar to that of the wind ambiguities retrieved from conventional multi-look scatterometry measurements (e.g., SeaWinds). Thus, it would be reasonable to apply a similar median filtering ambiguity removal algorithm for active/passive ambiguities [11, 12]. This shows the potential of combining passive microwave measurements and single-look scatterometer measurement for future ocean surface wind vector retrievals.

TABLE IV
WIND DIRECTION RETRIEVAL SKILL

<table>
<thead>
<tr>
<th>Wind Speed (meter/sec)</th>
<th>Closest Ambiguity Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st</td>
</tr>
<tr>
<td>5</td>
<td>30%</td>
</tr>
<tr>
<td>7</td>
<td>30%</td>
</tr>
<tr>
<td>9</td>
<td>30%</td>
</tr>
<tr>
<td>12</td>
<td>61%</td>
</tr>
<tr>
<td>15</td>
<td>82%</td>
</tr>
<tr>
<td>20</td>
<td>91%</td>
</tr>
</tbody>
</table>

VII. CONCLUSION

A novel passive microwave wind vector model function was developed for the AMSR radiometer on the ADEOS-II satellite. This model function relates the linear combination of the vertical and horizontal \( T_B \)'s \( (A \cdot T_{BV} - T_{BH}) \) to the ocean surface wind vector and SST for AMSR 10, 18 and 37 GHz channels. This brightness temperature combination proved to be insensitive to the atmosphere and therefore is suitable for ocean surface wind vector retrievals. This AMSR \( A \cdot T_{BV} - T_{BH} \) model function is a function of SST, wind speed and a biharmonic cosine function of relative wind direction.

The major application of the \( AV-H \) model function is wind vector retrieval. Since the model function depends on both wind speed and direction, ultimately both of these parameters can be retrieved from these measurements. Further, improvements should be possible in other surface and atmospheric parameter retrievals because of the removal of the wind direction bias present in current passive microwave geophysical algorithms.

The use of the \( AV-H \) brightness temperature measurements alone may not be sufficient for retrieval of ocean surface wind vector to the required accuracy; however, when used with only forward-looking scatterometer measurements, good wind direction retrievals are possible. While linear combination of V- and H-pol measurements for two lower frequencies as obtained through derived \( AV-H \) in this paper represents good approximation for only surface dependent functions, however, 37 GHz channel combination still seem to be sensitive to slight changes in the atmosphere (Fig. 2). Results presented demonstrate that the selected “closest-alias” active/passive retrievals meet the wind direction measurement requirement of \( \pm 20^\circ \) (one sigma). Although these retrieval errors are significantly larger than the standard SeaWinds four-look scatterometer retrievals, considering the preliminary nature of this active/passive retrieval algorithm, the results are encouraging.

Further, this novel wind vector retrieval technique demonstrates an alternative option for future satellite missions. The integration of a single-look scatterometer with a conically scanning radiometer could retrieve wind vector over all wind speeds with a significant reduction in spacecraft accommodation complexity and hardware cost compared to two stand-alone instruments.
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REFERENCES


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