Ocean Surface Wind Retrieval Using Passive, Polarimetric Microwave Remote Sensing

John F. Vesecky
Electrical Engineering Department, University of California at Santa Cruz
221 Baskin Engineering, 1156 High Street, Santa Cruz CA 95064
phone: (831) 459-4099 fax: (831) 459-4829 email: vesecky@cse.ucsc.edu

Atmospheric, Oceanic and Space Science Department, University of Michigan
2455 Hayward Road, Ann Arbor MI 48109-2143
phone: (734) 764-5151 fax: (734) 764-5137 email: jfv@engin.umich.edu

Award Numbers: N00014-01-1-0263 (UCSC) and N00014-99-1-0174 (UM)

LONG-TERM GOAL

The long-term goal of this research is to develop a robust, physically based, and efficient algorithm for retrieving ocean surface wind vectors from fully polarimetric, passive microwave observations. This retrieval scheme would be applied to data from the Navy's WindSat and other passive microwave sensors of the future, such as the CMIS instrument on the NPOESS meteorological satellites.

OBJECTIVES

The objectives of this research build on existing work in a variety of publications by Lyzenga, Vesecky and Wang as well as work by others. We first seek to develop an advanced, physically based, forward passive/active microwave ocean model, with rough surface and foam effects. Testing of this forward model would be accomplished by comparing model predictions against existing satellite observations from SSM/I as well as aircraft observations by JPL (Windrad), Georgia Tech (PSR) and NRL. This model would work with an atmospheric radiative transfer model for microwave emissions and an inversion algorithm to retrieve ocean-surface wind vectors from polarimetric, passive microwave measurements. The retrieval algorithm would be tested and applied to WindSat observations.

APPROACH

Forward Model Improvements and Validation: The emphasis in the present investigation is on estimation of wind direction as well as wind speed from passive microwave measurements. To this end, an emissivity model is required that accurately predicts the dependence of the emitted radiation on azimuth angle, i.e., the angle between the line of sight of the sensor and the wind direction. To estimate how polarimetric brightness temperatures of the ocean surface will vary as functions of observational parameters, we have implemented a two-scale emissivity model based on the second-order small perturbation method (SPM). Our two-scale numerical model predicts the Stokes vector of thermal emission from randomly rough dielectric surfaces described by anisotropic directional ocean wave spectra. The forward model must be computationally efficient, as well as accurate, for operational wind retrievals. Hence, we have devoted significant time to speeding up our numerical model and have developed an even faster analytical model. Validation of the forward model has been

Report Documentation Page						*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **30 SEP 2002**	2. REPORT TYPE	3. DATES COVERED **00-00-2002 to 00-00-2002**

4. TITLE AND SUBTITLE **Ocean Surface Wind Retrieval Using Passive, Polarimetric Microwave Remote Sensing**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Electrical Engineering Department, University of California at Santa Cruz,,221 Baskin Engineering, 1156 High Street,,Santa Cruz,,CA, 95064**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The long-term goal of this research is to develop a robust, physically based, and efficient algorithm for retrieving ocean surface wind vectors from fully polarimetric, passive microwave observations. This retrieval scheme would be applied to data from the Navy???s WindSat and other passive microwave sensors of the future, such as the CMIS instrument on the NPOESS meteorological satellites.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a REPORT **unclassified**	b ABSTRACT **unclassified**	c THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

achieved through comparison with satellite and aircraft data and is continuing as new data become available. Current sources of satellite-microwave radiometer data include SSM/I and the microwave imager aboard the TRMM satellite. Airborne polarimetric radiometers include JPL's Windrad and the Georgia Tech/NOAA ETL Polarimetric Scanning Radiometer (PSR). We compared some of these data with our numerical model and found that there was more variation between the field data sets than between the field data and the model. We are working with NRL to use their field data in these comparisons.

Inversion Algorithm Development: Inversion methods must be both accurate and computationally efficient enough to allow operational wind retrievals in real time. Proper handling of the multi-valued nature of the derived wind vector estimates is also an important factor. We base our inversion methods on WindSat parameters, but make them flexible for application to other instruments, e.g. SSM/I and aircraft instruments. First, we seek accurate retrievals in test cases with simulated data sets and then examine performance using available data sets and empirical models.

WORK COMPLETED

1. *Development of analytical forward model* by approximation of the needed integral using series expansions of integrands. Several orders of magnitude speed increase has been achieved.

2. *Retrieval algorithm analysis and evaluation* through simulations has shown that large errors at relatively high wind speeds, e.g., 15 m/s, can result through failure of an inversion algorithm to locate all solutions of a given inversion and thus selection of an incorrect solution.

3. *Mitigation of large errors in inversion estimates has* been achieved through modifications in algorithm design led by analysis of characteristics of ambiguities in the inversion. The modified algorithm employs a hybrid design using both downhill simplex optimization and coarse grid search techniques to ensure identification of all cost function minima and accurate wind vector estimation.

4. *Retrieval algorithm improvement and verification***:** Simulation experiments have been completed verifying that significant improvements have been obtained through our inversion algorithm modifications. Further analysis of algorithm performance is under way to examine the effects of various satellite and sea state parameters and system noise on the accuracy of vector wind retrievals.

5. *Reporting of our results* in journal publications and at major conferences, listed below

RESULTS

Analytical model for microwave emission from the sea surface: The microwave emissivity of the ocean surface is influenced by both the small-scale and the large-scale surface roughness. The two-scale model described by Yueh (1997) accounts for both length scales, but the large number of computations required for the four-dimensional integration for each Stokes parameter limits its usefulness for wind speed inversion algorithms that involve repeated model evaluations.

We have developed a simplified analytical model for the Stokes parameters describing the polarization properties of the microwave radiation emitted from the ocean surface. The Stokes parameters (T_v, T_h, U and V) are each expressed as a truncated Fourier series in the angle ϕ between the observation direction and the wind direction, *e.g.*, $T_v(\theta,\phi) = a_0 + a_1 \cos\phi + a_2 \cos 2\phi$. Algebraic expressions are derived for the Fourier harmonic coefficients (a_0, a_1, *etc*.) of the Stokes parameters as functions of the wind speed and the observational angle of incidence. This is accomplished by evaluating the slope integral in the two-scale emissivity model of Yueh (1997) analytically, after expanding the integrand as a Taylor series in the surface slope. The surface slope probability density functions are taken from Cox and Munk (1954) and the ocean wave height spectrum of Durden and Vesecky (1985) is used. Hydrodynamic modulation effects are included to model the upwind-downwind asymmetry in the Stokes parameters. Expressions are derived that allow variations of the four Stokes parameters to be computed as simple functions of the complex permittivity ε of the ocean surface, observational angle of incidence θ, wind direction ϕ and wind speed W. In Fig. 1 we show comparisons with airborne (PSR & Windrad) and space borne (SSM/I) measurements and with our numerical model. We think that this model will find useful application to passive microwave remote sensing of the ocean, in particular to wind retrieval algorithms and to instrument design and evaluation.

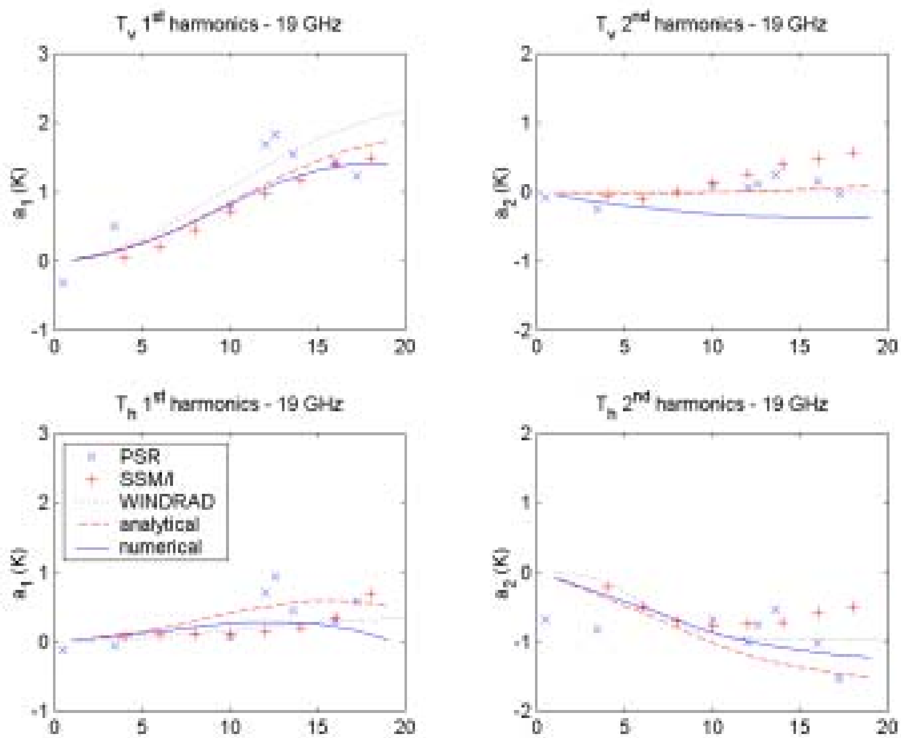

Figure. 1. Comparison of analytical and numerical models (lines) with experimental measurements (symbols) of the Fourier harmonics of the Stokes parameters for a frequency of 19 GHz and a wind speed of 10 m/s.

Inversion method, modifications and preliminary results: Inversion of microwave radiation measurements to obtain estimates of the near surface wind vector is facilitated by minimization of a cost function comparing the measured radiation to the radiation predicted for an assumed wind vector solution. This cost function is given by $f = \sum_i h_i \left(\hat{T}_{B_i} - T_{B_i}\right)^2$ where $\hat{T}_B$ is the measured brightness temperature, T_B is the predicted brightness temperature for a given estimate of the wind vector and h_i is a weighting factor based on the noise of the given channel (frequency, polarization and satellite look angle) denoted by the summation index, *i*. In general, the cost function will contain multiple minima and the global minimum will reliably correspond to the true solution only if the noise is sufficiently low. In order to achieve optimal performance, an inversion algorithm must locate all minima of the cost function. The wind vector estimates corresponding to each minimum may then be evaluated to determine which one is most likely to be the best estimate of the true solution.

Our initial algorithm design addressed this issue of multiple minima by repeating the minimization process for four different wind direction initial points (0, 90, 180, and 270 degrees). If the ambiguous solutions corresponding to the multiple minima were separated from the true minimum by approximately 180 degrees, then such an algorithm would be effective in locating all minima of the cost function. In-depth analysis of the cost function, however, demonstrated that this was not the case, but rather that the deviations of the ambiguous solutions relative to the true solution have a complicated dependence on the true solution. The results of this analysis for wind direction deviations are shown in Fig. 2. Further, simulation experiments revealed that anomalously high errors in both wind speed and direction resulted for certain cases of the true wind vector. It was found that these errors were due to the algorithms failure to locate all minima of the cost function and hence, selection of false minima.

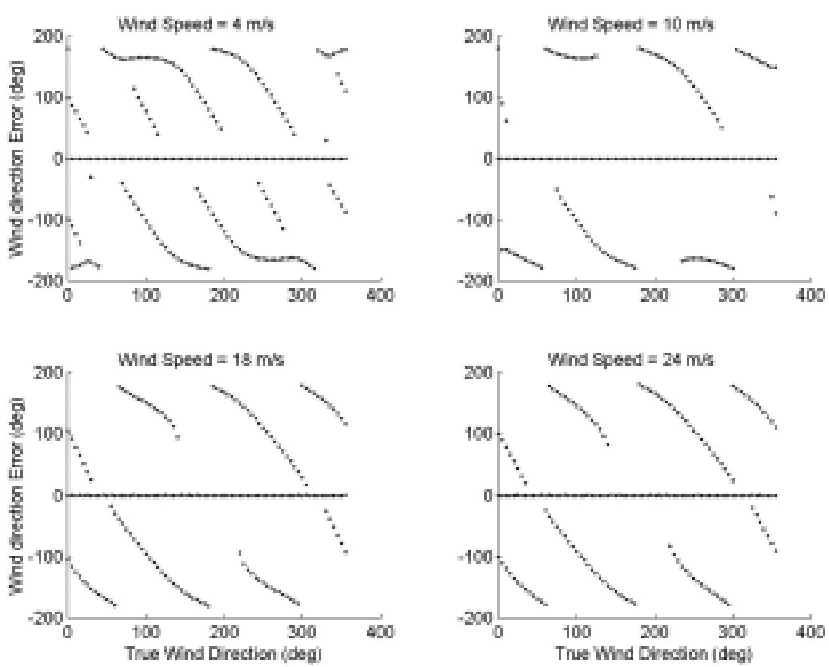

Figure 2. Plots of wind direction error associated with all cost function minima as a function of true wind direction relative to satellite look angle for 4, 10, 18 and 24 m/s wind speeds. In each plot, the horizontal line of points at zero wind direction error corresponds to the minimum of the cost function at the true solution. All other points correspond to false minima of the cost function.

Modifications were made to our initial algorithm to address problems caused by failure to locate all cost function minima. The modified algorithm employs a hybrid design using both downhill simplex optimization and grid search techniques. A coarse grid search is first used to roughly locate all minima of the cost function. The grid search results are then used to initialize the simplex search method used to refine each coarse estimate. In this way all minima are precisely located while computational efficiency is retained by keeping the number of simplex minimizations to a minimum.

A comparison between the rms error in wind speed and direction results for the original algorithm and the modified algorithm is shown in Figure 3. The results were obtained using simulations of 37 GHz polarimetric radiometer measurements from 55 degrees incidence with a true wind speed of 20 m/s and an assumed Gaussian noise in the measurements of 0.2 K. In the results for the original algorithm, large errors for true wind directions near 355 degrees are due to failure of the algorithm to locate all cost function minima. It can be seen that the modifications to the algorithm have been effective in reducing these errors. While these results are preliminary, we anticipate that they will aid in algorithm design for making useful predictions for WindSat and other future instruments.

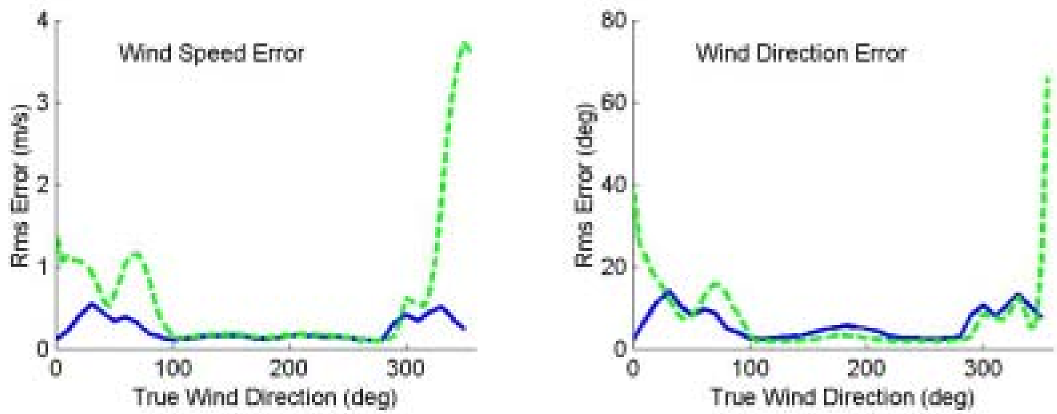

Figure 3. Plots of rms wind speed and direction errors as a function of true wind speed for both the original algorithm (green, dashed line) and the modified algorithm (blue, solid line). True wind speed was 20 m/s.

IMPACT/APPLICATION

The impact of an accurate physical model for active and passive microwave characteristics of the ocean surface would be truly striking. While empirical models are very useful, they are limited to the environmental and observational conditions under which the data were collected and unmodeled variables are likely to cause errors. Hence, an accurate physical model could relieve some limitations on operational wind retrievals. The most important impact of our research would be in providing accurate wind field retrievals for the WindSat satellite, as well as other future active and passive microwave sensors. In addition, an accurate microwave ocean model would be useful for instrument design, estimating errors and for interpolating and extrapolating empirical data for empirical model functions. Our efforts in the area of algorithm development may help to further illuminate the potential problem of large errors or unreliable results due to the presence of ambiguous solutions and suggest a partial solution to the problem that is both effective and reasonably efficient computationally.

TRANSITIONS

We anticipate that our work will transition to the meteorological remote sensing community to enable more accurate wind vector retrievals for the Navy's WindSat and other future satellite sensors.

RELATED PROJECTS

The most important related project is the Navy's WindSat project that will launch a fully polarimetric passive microwave sensor in December 2002.

PUBLICATIONS AND PRESENTATIONS

Lettvin, E.E. & J.F. Vesecky, Estimation of wind friction velocity & direction at the ocean surface from physical models & space-radar scatterometer measurements, **J. Geophy. Res., Oceans, 106**, C 10 22,503-519 (2001)

Lyzenga, D. and J.F. Vesecky, An analytical two-scale model for the microwave emissivity of the ocean surface, submitted to **IEEE Trans. Geosci. and Remote Sens.** (2002)

Lyzenga, D., J.F. Vesecky and N-Y Wang, An analytical two-scale model for the microwave emissivity of the ocean surface, **2001 IEEE AP-S/URSI Symposium**, Boston MA, July (2001)

Wang, N-Y, D. Lyzenga and J.F. Vesecky, Ocean surface wind vector estimation using passive microwave remote sensing, **IGARSS '01**, Sydney, Australia, July (2001)

Wang, N-Y and J.F. Vesecky, Sea surface temperature and wind field estimation using active /passive microwave remote sensing, to be submitted to **IEEE Trans. Geosci. Remote Sens.** (2002)

Laws, K.E., D. Lyzenga, J. Vesecky and D. Wiberg, Estimation of the error variance of vector wind estimates from fully polarimetric measurements of ocean surface brightness temperature, Oral presentation, **American Geophysical Union, Ocean Sciences Meeting** (2002)