Hurricane Wind Vector Estimates from WindSat Polarimetric Radiometer

Ian S. Adams
Microwave Remote Sensing Consultants
Naval Research Lab
Washington, DC, USA
ian.adams@nrl.navy.mil

Christopther C. Hennon
University Corporation for Atmospheric Research
Tropical Prediction Center
Miami, FL, USA
Christopher.Hennon@noaa.gov

W. Linwood Jones and Khalil Ahmad
Microwave Remote Sensing Consultants
Cocoa Beach, FL, USA
ljones5@cfl.rr.com

***Abstract*—WindSat is the world's first microwave polarimetric radiometer, designed to measure ocean vector winds. In late 2004, the first preliminary oceanic wind vector results were released, and this paper presents the first evaluation of this product for several Atlantic hurricanes during the 2003 season. Both wind speed and wind direction comparisons will be made with surface wind analysis (H*Wind) developed by the NOAA Hurricane Research Division (HRD) and provided by the NOAA National Hurricane Center (NHC). Examples are presented where HRD aircraft flights were conducted within several hours of the WindSat overpass. These H*Wind surface wind analyses provide the most complete independent surface winds comparison data set available. Both WindSat retrieved wind speeds and wind directions are evaluated (against H*Wind) as a function of storm quadrant. To complement the analysis, rain rates were derived using WindSat brightness temperatures with a modified version of the TMI 2A12 heritage rain algorithm. Effects of rain on the derived wind speeds and directions are discussed.**

I. INTRODUCTION

WindSat is the first space-borne microwave polarimetric radiometer, launched on the Coriolis near-polar LEO satellite in January 2003. As a proof-of-concept mission, the objective of WindSat is to develop and demonstrate passive ocean wind vector retrieval from space as risk reduction for the upcoming Conical Scanning Microwave Imager/Sounder (CMIS), planned for launch in late 2009. Following the heritage of seven Special Sensor Microwave/Imagers (SSM/I), WindSat provides retrievals of atmospheric and ocean environmental parameters such as total cloud liquid water, integrated water vapor, wind speed and, additionally, sea surface temperature. The focus of WindSat, however, is to provide the first passive wind direction measurements from space. Currently, two preliminary six-month data sets of WindSat retrievals are available: an empirically derived product from NOAA/NESDIS [1,2] and a physics-based product from the Naval Research Lab [3]. Both products demonstrate that passive wind vector retrievals are feasible [4].

Ocean vector wind data is vital in understanding global climate change, air-sea interaction and atmospheric circulation. Of special interest to meteorologists is the ability of space-borne instruments to sense tropical cyclones (TC) in openocean where other instruments, such as buoys, are unavailable. While scatterometer measurements, including those from QuikSCAT, have been introduced into numerical models used for forcasting hurricanes, there has only been limited success due to the detrimental effects of high rain on scatterometer retrievals.

The objective of this paper is to analyze the suitability of passive ocean wind vector measurements in TCs. Version-0 wind retrievals produced by National Oceanographic and Atmospheric Administration National Environmental Satellite, Data and Information Service (NOAA/NESDIS) are compared to an experimental surface wind analysis, H*Wind for two passes from 2003. The correlation of wind retrieval error with rain is also investigated.

II. PASSIVE MICROWAVE POLARIMETRY

The microwave ocean brightness temperature (Tb) scene observed by a radiometer depends upon various atmospheric and ocean surface geophysical variables, as well as a number of instrument parameters. Since the Tb signatures are functions of the radiometer frequency (wavelength) and polarization, the separation of these effects allow for multi-frequency radiometer geophysical retrievals process [5]. Of special interest are the signatures of ocean wind vectors. Recent advances in polarimetric radiometry modeling and measurements have demonstrated that usable wind direction information can be obtained by combining the vertical and horizontal polarizations with the cross-correlation of the two [6]. The cross correlation terms represent the third and fourth parameters of the modified Stokes vector [7], defined as

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **25 JUL 2005**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Hurricane Wind Vector Estimates from WindSat Polarimetric Radiometer**		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) **Microwave Remote Sensing Consultants Naval Research Lab Washington, DC, USA**		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
See also ADM001850, 2005 IEEE International Geoscience and Remote Sensing Symposium Proceedings (25th) (IGARSS 2005) Held in Seoul, Korea on 25-29 July 2005. , The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**4**	

$$I_s = \begin{matrix} I \\ Q \\ U \\ V \end{matrix} = \begin{matrix} T_v \\ T_H \\ T_{+45} - T_{-45} \\ T_{lc} - T_{rc} \end{matrix} = \begin{matrix} \langle E_v E_v^* \rangle \\ \langle E_h E_h^* \rangle \\ 2\,\mathrm{Re}\langle E_v E_h^* \rangle \\ 2\,\mathrm{Im}\langle E_v E_h^* \rangle \end{matrix} \quad (1)$$

In this definition, T_v, T_h, T_{+45}, T_{-45}, T_{lc} and T_{rc} represent brightness temperature (radiances) at vertical, horizontal, plus 45^0, minus 45^0, left-hand circular and right-hand circular polarizations respectively. In principle, the Stokes vector provides a full characterization of the electromagnetic signature of the ocean surface, which is sufficient to uniquely determine the wind direction.

The 3rd (implemented by the difference between the ±45° polarization channels) and the 4th (implemented by the difference between the left and right-hand circular polarization channels) Stokes parameters offer the most wind direction information. On WindSat, there are three channels there are three polarimetric channels available: 10.7 GHz, 18.7 GHz and 37 GHz. Both the 3rd and 4th Stokes signatures are relatively weak as environmental radiometric signals go; but, fortunately, they are very robust in that they are highly immune to the influences of atmospheric absorption and emission caused by water vapor and cloud liquid water. These atmospheric signals are common-mode and cancel during the subtraction of the ±45° and left and right-hand circular polarizations. Unfortunately the effect of heterogeneous precipitation is less certain because there are an extremely limited number of observations of the 3rd and 4th Stokes parameters in the presence of rain. Since strong bands of precipitation accompany hurricane winds, an analysis of the effects of rain on hurricane retrievals is presented in this paper.

III. DATA SETS

A. WindSat Wind Vector Retrievals

This paper contains an analysis of the WindSat NOAA/NESDIS version-0 wind vector retrieval algorithm [1,2] within TCs. Since Tb channels are of different resolution and geolocation, brightness temperatures are resampled to every fourth 37 GHz location and beam averaged to the resolution of 6.8 GHz channel, resulting in a spatial resolution of approximately 50 km at 12.5 km spacing in both the along- and cross-track directions. The first step in this wind retrieval process is to process the four-frequency, vertically and horizontally polarized WindSat Tb's in a similar manner to the procedure implemented for SSM/I [8] to solve for four relevant environmental variables (not including wind direction). A forward radiative transfer model provides the relationship between the measured Tb's (over oceans) and a variety of environmental parameters. Of these environmental parameters, the four that can be retrieved are sea surface temperature (SST), surface wind speed (WS), integrated atmospheric water vapor (WV), and integrated cloud liquid water (CLW). Using regression coefficients derived from the forward model, the retrieval algorithm sequentially solves first for the CLW (using the 18.7, 23.8 and 37.0 GHz), then WV (using same channels), next WS (10.7, 18.7, 23.8 and 37.0 GHz), and finally SST (using only 10.7 GHz). After resolving these four parameters, the entire process is iterated several times until the retrievals converge to a stable value. It should be noted that this environmental retrieval algorithm does not include the effects of rain, nor has it been developed for winds > 20 m/s.

The retrieved wind speeds are then used, along with the 10.7, 18.7 and 37 GHz 3rd and 4th Stokes parameters, for wind direction retrieval. Relative wind directions are varied and modeled 3rd and 4th Stokes parameters, $(T_{U,V})^{mod}$ are calculated. For each relative wind direction trial, the square of the difference between the measured and the modeled parameters $\{(T_{U,V})^{meas}$, and $(T_{U,V})^{mod}\}$ is calculated and summed for all frequencies. Values of relative wind direction that minimize the sum of these terms for all frequencies are "possible solutions". Due to the harmonic nature of the 3rd and 4th Stokes parameters, retrievals results in multiple possible wind directions (called wind direction aliases or ambiguities). Aliases are ranked inversely proportional to the cost function. After ranking, the aliases subjected to a multi-pass median filter to produce a single selected vector. The alias selection skill, which is defined as the percentage of the selected directions that are closest to the true direction, is typically > 85%.

B. WindSat Derived Rain Rates

To aid in the evaluation of hurricane wind retrievals, we derive rain rates using a preliminary WindSat rain algorithm. The algorithm is based on a modified version of the Goddard Profiling Algorithm (GPROF) currently being used with the Advanced Microwave Scanning Radiometer – Earth Observing System (AMSR-E) [8,9]. GPROF is a multi-channel, physically based rainfall rate retrieval algorithm employing cloud-resolving models to produce a large number of cloud profiles for various rain conditions. Brightness temperatures are produced using a forward model and are then convolved with the antenna patterns of the various frequencies generating modeled Tbs for each of the utilized channels. Once the database of profiles and respective Tbs is established, rainfall rates are estimated, on a pixel-by-pixel basis, using a Baysian inversion, given the set of measured brightness temperatures.

For rain retrieval, WindSat brightness temperatures are resampled to every fourth 37 GHz location using an average of the four nearest neighbors with a $1/R^2$ weighting. This effectively yields a 12.5 km by 12.5 km grid, on which each channel retains its inherent resolution. Four frequencies and seven channels are used: 10.7, 18.7, 37 GHz (vertical and horizontal), and 23.8 GHz (vertical only). Typically GPROF uses both 37 GHz and high-resolution 85 GHz brightness temperatures to classify rain events as convective or stratiform. Since the 85 GHz channel is not available, the WindSat algorithm depends only on the emission characteristics of the 37 GHz channel to assess the type of rain event [10].

*C. H*Wind Modeled Wind Fields*

Due to the poor temporal and spatial sampling of hurricanes, verification of TC surface winds is inherently difficult; however, with data available from airplane reconnaissance missions, reasonable analyses are possible. The H*Wind [11] analysis system is a software tool, developed by NOAA's Hurricane Research Division (HRD), that assimilates these aircraft measurements, along with surface measurements and remotely sensed satellite data into a common model that allows for limited human quality control. There are some caveats associated with using H*Wind data. H*Wind is not an instantaneous view of a TC, but an assimilation of data over a period of three to six hours. Also, much of the storm it not observed over this time frame. Due to the high temporal and spatial variability of TC wind field structures, there is a significant error range—on average 10% to 20% for wind speed [12]. Additionally, the under-sampling of TCs results in maximum wind estimates that are typically lower than the actual intensity.

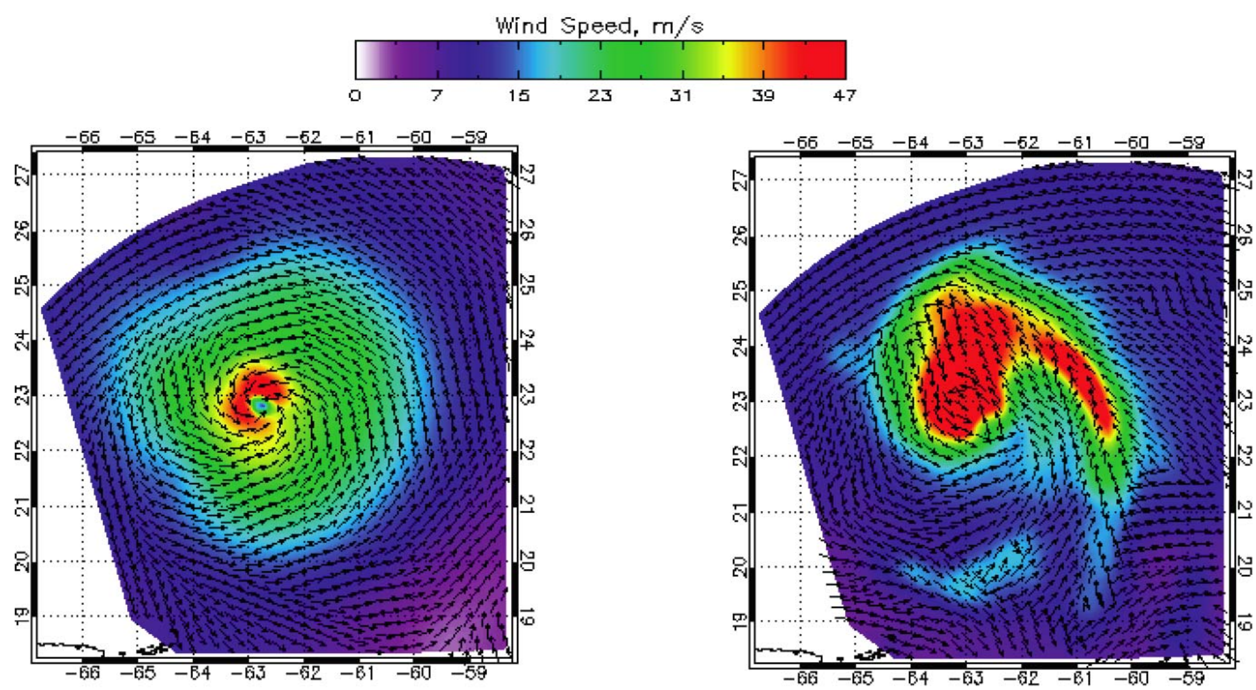
IV. Analysis

For this paper, two cases from 2003 are carefully chosen where the TCs have been well sampled by air reconnaissance close to the respective WindSat passes: Fabian on 3 September 2147 UTC and Isabel on 17 September 1040 UTC. Using National Hurricane Center (NHC) "best-track" data, the centers of the H*Wind analyses have been shifted in time to match the storm centers at WindSat pass time. To match the spatial resolution and geolocation of WindSat wind vectors and H*Wind fields, a nearest-neighbor interpolation is performed, averaging all H*Wind data within a 25 km of radius of each WindSat measurement. Since the objective of this paper is to determine the potential of WindSat to make reasonable wind direction estimates hurricane, and not to evaluate selection skill, all analysis compares the WindSat directional alias that is closest to the H*Wind direction.

Fig. 1 shows a visual comparison between the H*Wind wind field (a) and the WindSat retrieval (b) for Hurricane Fabian 3 September 2147 UTC. WindSat wind speeds in the northern region of the storm are obviously biased high, while retrievals to the south of the eye are biased low. If we look at Fig. 4, we see that the overestimates of wind speed correlate well with areas of intense rain. Again, from an objective analysis, wind direction retrievals also seem to suffer from rain contamination. While WindSat does seem to represent the overall circulation of the TC well, there are some regions, even without rain contamination, where WindSat does a poor job of resolving the general flow, such as on the southeast side of the storm. In Fig. 5, a quantitative analysis demonstrates a high, almost linear, correlation of error wind speed (a) and direction (b) versus rain rate. RMS errors for speed and direction are 6.64 m/s and 29.7^0 respectively.

V. Conclusion

Using a two cases from the 2003 hurricane season, this paper takes a first look at evaluating the performance of WindSat hurricane wind vector retrievals. Comparisons of wind speeds demonstrate that the version-0 algorithm does not perform well for high wind and high rain conditions.



(a) (b)

Figure 1. Hurricane Fabian 2003 3 September 2147 UTC. (a) is H*Wind surface analysis. (b) is WindSat wind retrieval.

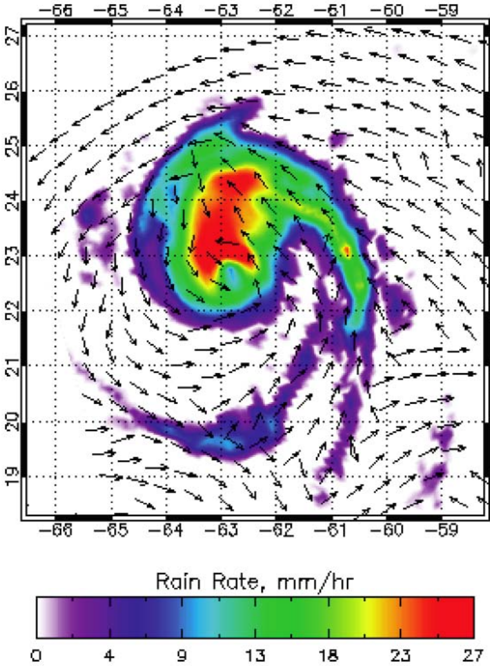


Figure 3. Hurricane Fabian 2003 3 September 2147 UTC. WindSat wind directions superimposed over WindSat rain rates.

While the performance of wind directions is slightly better, there still are major deficiencies in WindSat's ability to measure wind direction in the presence of rain. We are encouraged, however, that WindSat is able to make retrievals in heavy rain. Previous radiometers, such as SSM/I do not make wind speed retrievals in the presence of rain, and traditional scatterometer wind vector retrievals in hurricane conditions are highly suspect. Since the version-0 algorithm was developed only for rain free wind retrievals at < 20 m/s, we feel that further algorithm development will only improve WindSat's ability to retrieve wind vectors in turbulent weather conditions, such as those found in hurricanes.

Acknowledgment

The authors would like to thank Dr. Richard Knabb (Tropical Prediction Center) Dr. Mark Powell (Hurricane Research Division). Many thanks to Dr. Chris Kummerow for help in applying the AMSR-E rain algorithm to WindSat.

References

[1] Z. Jelenak, "WindSat polarimetric brightness temperature measurements: Part I: An empirical model," Unpublished.

[2] ——, "Windsat polarimetric brightness temperature measurements: Part II - Ocean surface wind vector retrievals," Unpublished.

[3] M.H. Bettenhausen, C.K. Smith, R.M. Bevilacqua, N.-Y. Wang, P.W. Gaiser, and S. Cox, "A nonlinear optimization algorithm for WindSat M.H. Freilich and B.A. Vanhoff, "The accuracy of preliminary WindSat vector wind measurements: comparisons with NDBC buoys and QuikSCAT," Unpublished.

[4] F.J. Wentz, A well-calibrated ocean algorithm for SSM/I, *J. Geophys. Res.,102,* 8703-8718, 1997.

[5] P.S. Chang, P.W. Gaiser, L. Li, and K.M. St. Germain, "Multi-frequency polarimetric microwave ocean wind direction retrievals," *Proceedings of the International Geoscience and Remote Sensing Symposium 1997*, Singapore, 1997.

[6] L. Tsang, J.A. Kong and R.T. Shin, *Theory of Microwave Remote Sensing*, New York: John Wiley and Sons, 1985.

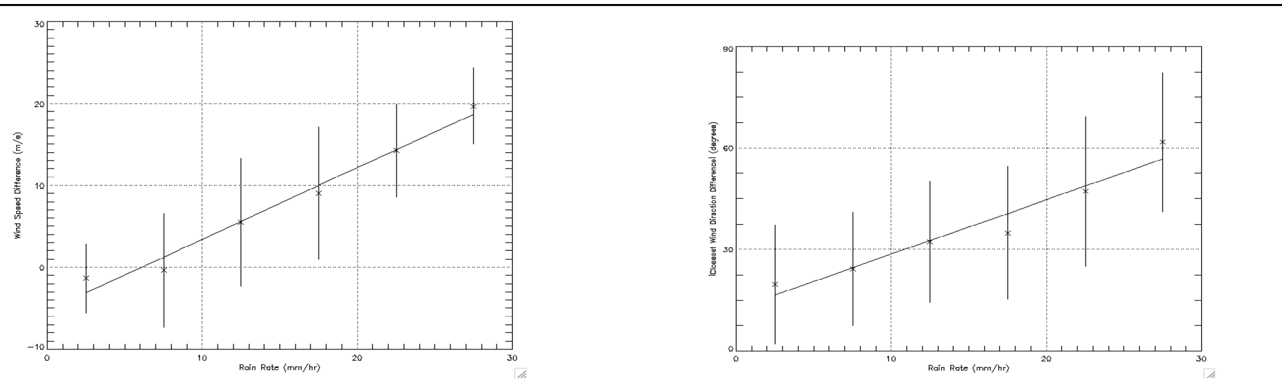
[7] C. Kummerow, W. Olson, and L. Giglio, "The evolution of the Goddard Profiling Algorithm (GPROF) for rainfall estimation from passive microwave sensors," *IEEE Transactions on Geosciences and Remote Sensing*, Vol. 34: 1213-1232, 1996.

[8] T. Wilheit, C. Kummerow, and R. Ferraro, "Algorithm Theoretical Basis Document for EOS/AMSR Rainfall," College Park, TX, USA, Texas A&M University, 1999.

[9] K. Ahmad, W.L. Jones, J. Thomas-Stahle, and C. Kummerow, "Oceanic rain rates from the WindSat Radiometer," IGARSS05, July 25-29, 2005.

[10] Powell, M.D., S.H. Houston, L.R. Amat, and N. Morisseau-Leroy, "The HRD real-time hurricane wind analysis system," *Journal of Wind Engineering and Industrial Aerodynamics.* vols. 77 & 78, pp 53-64, 1998.

[11] Houston, S.H., W.A. Shaffer, M.D. Powell, and J. Chen, "Comparisons of HRD and SLOSH surface wind fields in hurricanes: Implications for storm surge modeling," *Weather and Forecasting*, vol 14, pp 671-686, 1999.



(a) (b)

Figure 5. Scatter plots of wind speed error (a) and wind direction error (b) as a function of rain rate. X represents mean error for each 2.5 mm/hr bin of rain rate. Error bars denote +/- 1 standard deviation. Diagonal is linear regression.