CROSS-POLARIZED C-BAND SEA-SURFACE NRCS OBSERVATIONS IN EXTREME WINDS

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ABSTRACT

We report on airborne measurements of the cross-polarized (VH) ocean surface normalized radar cross-section (NRCS) at incidence angles between 15° and 40° obtained at C-band in high-wind ($> 30\,\mathrm{m\,s^{-1}}$) conditions. The present observations were taken in Hurricane Patricia on 23 October 2015 and extend the wind speed range of the existing cross-polarization ocean surface NRCS literature [1]–[4]. The NRCS at the smaller incidence angles decrease as wind speed increases, as expected. At the larger incidence angles, saturation of the NRCS is not observed up to at least $70\,\mathrm{m\,s^{-1}}$. The results have implications for planned and future scatterometers (e.g., MetOp-SG) that aim to increase the maximum observable wind speeds.

Index Terms— Radar remote sensing, airborne radar, radar cross-sections, sea measurements, C-band

1. INTRODUCTION

During the latter part of the 2015 hurricane season, the National Oceanic and Atmospheric Administration (NOAA)/National Environmental Satellite, Data, and Information Service (NESDIS) Ocean Surface Winds Team (OSWT) operated the Imaging Wind and Rain Airborne Profiler (IWRAP) from the NOAA WP-3D Hurricane Hunter aircraft. IWRAP [5] is a dual-frequency (C- and Ku-band) conically-scanning Doppler radar that was developed and is maintained by the Microwave Remote Sensing Laboratory (MIRSL) at the University of Massachusetts Amherst (UMass). For the present study, the C-band antenna spinning system was disabled and a prototype antenna for the next-generation MetOp-SG satellite scatterometer antenna [6] was installed. The antenna, designed by RUAG Space Sweden for the European Space Agency (ESA), was mounted at a 25° angle off aircraft nadir towards the right of the aircraft.

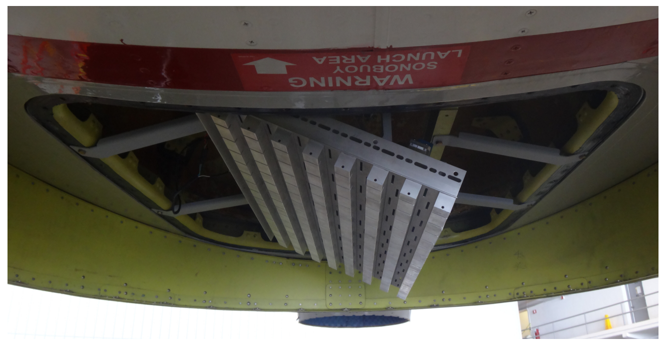

Fig. 1. An aft-looking picture of the ESA/RUAG antenna mounted on the NOAA WP-3D N43RF for the 2015 hurricane season. The Ku-band fairing, also without its radome, can be seen at the bottom of the picture.

Figure 1 shows an aft-looking picture of the antenna. This configuration provides a range of incidence angles from approximately 10° to 40° during level flight, with the lower incidence angles limited primarily by the 30 m range resolution of IWRAP.

The NOAA Aircraft Operations Center (AOC) operates the Stepped Frequency Microwave Radiometer (SFMR), developed by ProSensing, Inc. of Amherst, MA, that is used to retrieve surface wind speed and volume-averaged rain rate below the aircraft. It is a C-band nadir-pointing microwave radiometer that steps through six frequencies, dwelling at each for 0.5 s to make a brightness temperature ($\mathrm{T_b}$) measurement. This instrument has been installed on each of the NOAA WP-3D aircraft for all research flights since 2006. The operational geophysical model function (GMF) relating excess emissivity from the ocean surface to surface wind speed was recently revised [7] and is used in this analysis. Since the retrieval algorithm for SFMR is only reliable at nadir incidence, retrievals are only used from data collected at incidence angles within ±3°.

Recently the ocean vector wind sensing community has become interested in cross-polarized normalized

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radar cross-section (NRCS) measurements. Co-polarized NRCS at C-band from a wind-roughened, rain-free ocean surface is known to saturate at high wind speeds [8], [9]. Some studies using the C-band RADARSAT-2 synthetic aperture radar (SAR) instrument suggest that the cross-polarized (i.e., VH or HV) radar backscatter may not saturate at high wind speeds [10]–[12]. Other more theoretical works suggest that if there is signal saturation, it occurs at wind speeds higher than the co-polarized saturation wind speeds [2], [4].

The remainder of this paper presents initial findings from IWRAP, which was flown on the NOAA Hurricane Hunter flight through Hurricane Patricia during 23 October 2015. During this flight, Hurricane Patricia was at a Category 5 on the Saffir-Simpson Hurricane Wind Scale and later made landfall on the west coast of Mexico. During the final pass through the storm, the central pressure of Patricia was estimated to be 879 mbar based on a GPS dropwindsonde and the SFMR reported maximum surface winds in the eyewall of at least $85\,\mathrm{m\,s^{-1}}$ in real-time. Unfortunately, the highest winds were present in rainy conditions so NRCS in wind speeds above $75\,\mathrm{m\,s^{-1}}$ have been omitted here. The IWRAP C-band system, from which the data presented in this paper was collected, was configured to sequentially measure 126-pulse blocks of HH, VV, and VH polarizations during all flights through the storm. In the following two sections, we describe the analysis procedure for and preliminary results of an investigation into the cross-polarized ocean-surface NRCS measured during this flight.

2. METHODOLOGY

Though the IWRAP system was calibrated on the ground both before and after the hurricane season, a residual 0.43 dB NRCS offset was observed in the data with respect to the CMOD5.h GMF [13]. This bias was observed in the VV-polarized azimuthally-averaged NRCS during aircraft orbits performed during the same flight. The aircraft loitered in a rain-free region of relatively consistent winds of $20\,\mathrm{m\,s^{-1}}$ to $22.5\,\mathrm{m\,s^{-1}}$ for approximately 1 hour between eyewall penetrations due to the violent turbulence encountered in the first pass. Nearby SFMR T_b measurements made when the SFMR incidence angle was less than 3° (level flight) were used to retrieve surface wind speeds. The IWRAP VV NRCS at all available incidence angles were averaged in azimuth and subtracted (in dB) from the mean GMF NRCS to obtain the offset above. This constant offset was then added to NRCS at all polarizations and incidence angles.

As is common during eyewall penetrations, the nose of the aircraft was angled in order to maintain a track perpendicular to the wind direction. As a result, different range gates in the antenna fan-beam were projected onto the ocean surface at different locations in the storm's wind speed profile. To alleviate this problem, SFMR retrievals were collocated with IWRAP measurements by radial distance from the center fixes of the storm for each pass. The hurricane was partitioned into 1 km radial bins into which SFMR retrievals were placed with IWRAP NRCS measurements. The along-track coordinate of each range gate was calculated and collocated with SFMR measurements made directly beneath the aircraft. Though the hurricane was not perfectly circular and symmetric, this method avoids assigning high wind speeds to low NRCS near the eyewall.

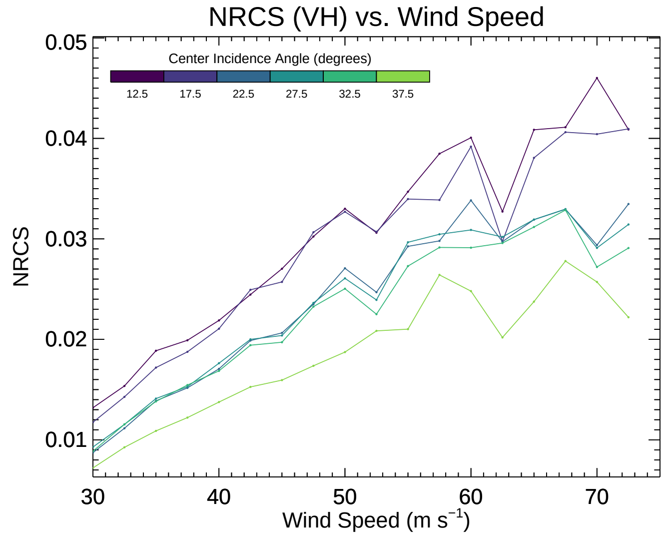

Fig. 2. Cross-polarized (VH) NRCS in linear units as a function of SFMR wind speed measured during the eyewall penetrations of Hurricane Patricia on 23 October 2015. Six averages over 5° of incidence angle are shown with the magnitude of NRCS generally decreasing with increasing incidence angle. NRCS is assumed to be independent of relative wind direction at these speeds. SFMR wind speeds were collocated with IWRAP measurements in along-track distance to account for the drift angle of the aircraft through the eyewall.

After collocation, NRCS was grouped into $2.5\,\mathrm{m\,s^{-1}}$ wind speed bins and 5° incidence angle bins. Here we assume that there is no wind-relative azimuth dependence above 30°, so we do not group at all by azimuth. The weak wind-direction dependence at these wind speeds is supported by recent IWRAP cross-polarization observations below $30\,\mathrm{m\,s^{-1}}$ (paper in review) and others [2], [4].

3. RESULTS

Figure 2 shows the VH NRCS dependence on wind speed above $30\,\mathrm{m\,s^{-1}}$. The NRCS is shown in linear units for six incidence angle ranges between 10° and 40°. As the wind speeds are above $30\,\mathrm{m\,s^{-1}}$, the NRCS likely does not have a significant wind direction dependence. The wind speed gradients through the eyewall at the higher speeds was steep, resulting in fewer samples and greater uncertainty than at the lower ($< 60\,\mathrm{m\,s^{-1}}$) wind speeds. There appears to be no saturation at all incidence angles up to at least $60\,\mathrm{m\,s^{-1}}$. The samples above this wind speed are too sparse to draw conclusions. Additionally, the SFMR is rarely operated in such conditions so the GMF in this regime is less certain.

4. CONCLUSIONS

Cross-polarized ocean surface NRCS was observed at C-band by the IWRAP scatterometer in rain-free conditions up to $75\,\mathrm{m\,s^{-1}}$ in Hurricane Patricia at several incidence angles between 10° and 40°. Patricia was the most intense tropical cyclone in the Western Hemisphere on record and presented a unique opportunity to investigate the VH ocean surface NRCS response to wind speeds above $30\,\mathrm{m\,s^{-1}}$. NRCS at the lower incidence angles appear to be more sensitive to wind speed than that at the larger incidence angles. There appears to be no saturation at any of these incidence angles up to $60\,\mathrm{m\,s^{-1}}$; higher SFMR wind speeds need to be further verified. The higher incidence angles ($\geq 25°$) may be showing some saturation effects at about $60\,\mathrm{m\,s^{-1}}$. Both IWRAP and SFMR data from this storm needs to be further analyzed to better understand the state of the ocean under extreme wind conditions.

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6. REFERENCES

[1] A. Mouche and B. Chapron, "Global C-Band Envisat, RADARSAT-2 and Sentinel-1 SAR measurements in copolarization and cross-polarization," *Journal of Geophysical Research: Oceans*, Nov. 2015. DOI: 10.1002/2015JC011149.

[2] F. Fois, P. Hoogeboom, F. Le Chevalier, and A. Stoffelen, "Future Ocean Scatterometry: On the Use of Cross-Polar Scattering to Observe Very High Winds," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 53, no. 9, pp. 5009–5020, Sep. 2015. DOI: 10.1109/TGRS.2015.2416203.

[3] P. A. Hwang, A. Stoffelen, G.-J. van Zadelhoff, W. Perrie, B. Zhang, H. Li, and H. Shen, "Cross-polarization geophysical model function for C-band radar backscattering from the ocean surface and wind speed retrieval," *Journal of Geophysical Research: Oceans*, vol. 120, no. 2, pp. 893–909, Feb. 2015. DOI: 10.1002/2014JC010439.

[4] G.-J. van Zadelhoff, A. Stoffelen, P. W. Vachon, J. Wolfe, J. Horstmann, and M. Belmonte Rivas, "Retrieving hurricane wind speeds using cross-polarization C-band measurements," *Atmospheric Measuring Techniques*, vol. 7, no. 2, pp. 437–449, Feb. 7, 2014. DOI: 10.5194/amt-7-437-2014.

[5] D. E. Fernandez, E. M. Kerr, A. Castells, J. R. Carswell, S. J. Shaffer, P. S. Chang, P. G. Black, and F. D. Marks, "IWRAP: The Imaging Wind and Rain Airborne Profiler for remote sensing of the ocean and the atmospheric boundary layer within tropical cyclones," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 43, no. 8, pp. 1775–1787, Aug. 2005. DOI: 10.1109/TGRS.2005.851640.

[6] P. Magnusson, P. Dimming, C. Lin, and A. Østergaard, "A thermally stable dual-polarized waveguide array," in *2015 9th European Conference on Antennas and Propagation (EuCAP)*, Lisbon, Portugal, Apr. 2015.

[7] B. W. Klotz and E. W. Uhlhorn, "Improved Stepped Frequency Microwave Radiometer Tropical Cyclone Surface Winds in Heavy Precipitation," *Journal of Atmospheric and Oceanic Technology*, vol. 31, no. 11, pp. 2392–2408, Nov. 2014. DOI: 10.1175/JTECH-D-14-00028.1.

[8] D. E. Fernandez, J. R. Carswell, S. Frasier, P. S. Chang, P. G. Black, and F. D. Marks, "Dual-polarized C- and Ku-band ocean backscatter response to hurricane-force winds," *Journal of Geophysical Research*, vol. 111, C8 2006. DOI: 10.1029/2005JC003048.

[9] J. Sapp, P. Chang, Z. Jelenak, S. Frasier, and T. Hartley, "Sea-surface NRCS observations in high winds at low incidence angles," in *Geoscience and Remote Sensing Symposium (IGARSS), 2015 IEEE International*, Jul. 2015, pp. 1199–1202. DOI: 10.1109/IGARSS.2015.7325987.

[10] P. W. Vachon and J. Wolfe, "C-Band Cross-Polarization Wind Speed Retrieval," *IEEE Geoscience and Remote Sensing Letters*, vol. 8, no. 3, pp. 456–459, 2011. DOI: 10.1109/LGRS.2010.2085417.

[11] B. Zhang, W. Perrie, and Y. He, "Wind speed retrieval from RADARSAT-2 quad-polarization images using a new polarization ratio model," *Journal of Geophysical Research*, vol. 116, Aug. 4, 2011. DOI: 10.1029/2010JC006522.

[12] J. Horstmann, S. Falchetti, C. Wackerman, S. Maresca, M. J. Caruso, and H. C. Graber, "Tropical Cyclone Winds Retrieved From C-Band Cross-Polarized Synthetic Aperture Radar," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 53, no. 5, pp. 2887–2898, May 2015. DOI: 10.1109/TGRS.2014.2366433.

[13] S. Soisuvarn, Z. Jelenak, P. S. Chang, S. O. Alsweiss, and Q. Zhu, "CMOD5.H—A High Wind Geophysical Model Function for C-Band Vertically Polarized Satellite Scatterometer Measurements," *IEEE Transactions on Geoscience and Remote Sensing*, pp. 1–17, Nov. 22, 2012. DOI: 10.1109/TGRS.2012.2219871.