C-BAND CROSS-POLARIZATION OCEAN SURFACE OBSERVATIONS IN HURRICANE MATTHEW

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ABSTRACT

In this paper, airborne measurements of the ocean surface normalized radar cross-section (NRCS) taken at co- and cross-polarizations in high-wind conditions are reported. The measurements were taken in Hurricane Matthew during which it was a Category 4 hurricane on the Saffir-Simpson Hurricane Wind Scale. Saturation of the co-polarized NRCS and lack of saturation in the cross-polarized NRCS is observed, consistent with previous results. The results have implications for planned and future scatterometers (e.g., MetOp-SG) that aim to increase the maximum observable wind speeds by using cross-polarized measurements.

***Index Terms*—** Sea measurements, C-band, scatterometry, remote sensing, cyclones

1. INTRODUCTION

In late September 2016, Hurricane Matthew formed near the Windward Islands. By 10 October, interactions with the coast of the Carolinas weakened it enough to dissipate. In the meantime it had passed between Cuba and Haiti and through The Bahamas, causing significant damage. It set the record for the southernmost category 5 hurricane in the Atlantic basin, reaching this intensity after a period of rapid intensification from 30 September to 1 October. [1]

On 1 October, the National Oceanic and Atmospheric Administration (NOAA)/National Environmental Satellite, Data, and Information Service (NESDIS)/the Center for Satellite Applications and Research (STAR) Ocean Surface Winds Team (OSWT) operated the the Imaging Wind and Rain Airborne Profiler (IWRAP) scatterometer [2] from the NOAA WP-3D Hurricane Hunter aircraft N43RF. The system was configured the same way as in [3]: a conically-scanning Ku-band antenna and a fixed side-looking C-band fanbeam antenna [4] mounted at 25° off nadir. In this paper we focus on the C-band measurements; its antenna, a prototype for the next-generation the European Space Agency (ESA) scatterometer, has an isolation sufficiently high to make cross-polarization measurements of the sea-surface NRCS possible. The IWRAP C-band acquisition system was configured for sampling HH, VV, and VH data sequentially during this flight.

Collocated on the aircraft and operated by NOAA Aircraft Operations Center (AOC) is Stepped Frequency Microwave Radiometer (SFMR) [5], a microwave radiometer used for remotely sensing ocean-surface wind speed and volume-integrated rain rate. It also operates at C-band, stepping through 6 frequencies over approximately 4 s and producing a retrieval every 1 s. The retrievals used in this manuscript are from geophysical model functions (GMFs) that are slightly modified from the current operational GMF [6] to improve agreement with dropsondes in the tropical environment (c.f. [7] for related work).

Scatterometer retrievals at high winds remain beyond the sensitivity capabilities of current technology; the backscattered co-polarized power saturates and even decreases in some situations [8], [9]. Cross-polarized sampling of the NRCS of the sea surface may be able to overcome some of these limitations, but few high-wind cases have been observed. An initial look at a case of extremely high winds suggested that the VH NRCS does not saturate at incidence angles common for scatterometers [3], however that data was only from a limited portion of that flight. Here we present more data collected in a similar manner for almost 5 h of flight time within a storm.

2. METHODOLOGY

Ground calibration of the IWRAP systems were performed before and after the hurricane season, but an in-flight calibration still needs to be performed. A small constant NRCS offset was observed in the VV-polarized data with respect to the CMOD5.h GMF [10] and was corrected for at all polarizations. For VV-polarization, measurements from a low-wind calibration flight were used to align measured NRCS with simulated NRCS. For HH-polarization, data were collocated with VV-polarized measurements taken at incidence angles less than 5° (i.e., during a right hand turn of at least 15°). Since the geophysical response should be the same, the mean

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measured difference was applied to HH-polarized NRCS to align the two. The correction for VH is simply the geometric mean of the co-polarized corrections (in linear units).

A polarization mixing correction was applied to VV, HH, and VH data following the procedure of [11] using mean simulated NRCS (A_0) only since a reliable source of surface wind direction was not available. This primarily affects the VH measurements at lower wind speeds. According to (B.27) in [11], if the VV and HH NRCS are in saturation (e.g., at high wind speeds) then any additional NRCS as wind speed increases is due to the VH backscatter. The effects on co-polarized NRCS are very small.

On entry and exit of the center of the hurricane, the nose of the aircraft was yawed 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 0.5 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 visibly elliptic on the aircraft's lower-fuselage radar, this method avoids assigning high wind speeds to low NRCS near the eyewall. Additionally, we located the maximum wind speed samples in the eyewall surrounding the eye and excluded data that were taken when the aircraft was within these locations.

3. RESULTS

Five incidence angles were chosen to represent the observations made during this flight: 20°, 25°, 30°, 35°, and 40°. Below 20°, the co-polarized NRCS is so strong at wind speeds below approximately $40\,\mathrm{m\,s^{-1}}$ that polarization mixing (due to the pitch angle of the aircraft) overwhelms the weak cross-polarized signal. Cross-polarized data above $40\,\mathrm{m\,s^{-1}}$ follow the same trend as the angles shown and the co-polarized data are nearly flat with wind speed at 15° and 10°, so the lower angles do not add much information. Higher incidence angles are not available in large quantities due to signal-to-noise ratio limitations. Above 40° incidence, the combination of the antenna gain sharply decreasing and the effect of range to the surface introduce large uncertainties. For all plots shown below, the range of the vertical axis is the same so relative levels of each can be compared.

Rain rates were limited assuming radial uniformity in the same way SFMR wind speeds were collocated with different incidence angles. Below $30\,\mathrm{m\,s^{-1}}$, the maximum allowed rain rate was allowed to be $5\,\mathrm{mm\,h^{-1}}$; above $30\,\mathrm{m\,s^{-1}}$, this allowance was increased to $20\,\mathrm{mm\,h^{-1}}$. The rationale is that at higher wind speeds, any splash effect on the ocean surface is

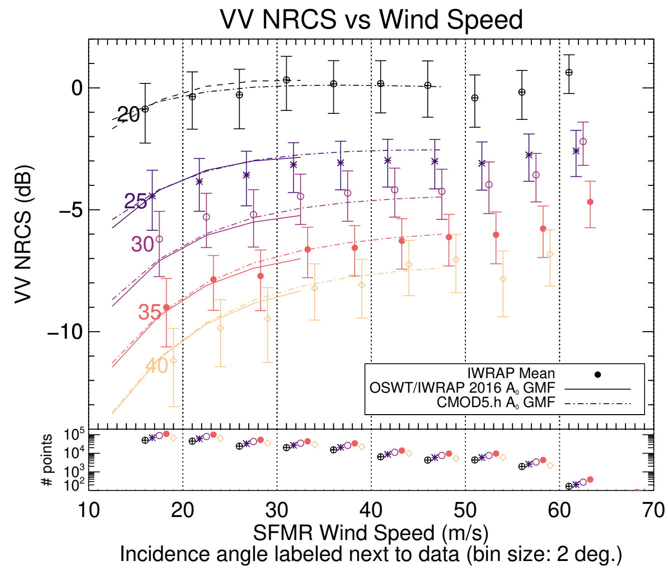

Fig. 1: Co-polarized (VV) NRCS in dB as a function of SFMR wind speed measured in Hurricane Matthew on 1 October 2016. Five sets of NRCS averages, each over 2° of incidence angle, are shown in the top panel with number of samples in the bottom panel. IWRAP means at the incidence angles and wind speeds shown are indicated by unconnected symbols. Each symbol is shifted slightly for clarity; the actual wind speed value it represents is the center of each wind speed bin. The interquartile standard deviations are shown as vertical bars. SFMR wind speeds were collocated with IWRAP measurements in along-track distance to account for the drift angle of the aircraft through the storm. Data taken from within the eyewall, in high rain rates, and at low SFMR wind speeds were excluded. Saturation at all incidence angles occurs at high winds.

likely to be overcome by the effect of the wind. SFMR rain rate sensitivity below $5\,\mathrm{mm\,h^{-1}}$ is low and, even when there is light rain, it will not affect the ocean surface statistics or the attenuation and scattering of a C-band signal.

Fig. 1 shows the VV-polarized NRCS response to SFMR surface wind speed at the five incidence angles. Each incidence angle includes data from ±1° around the nominal angle. No discrimination is made for surface wind direction since a reliable source is not available; hence there is a bit more scatter and uncertainty associated with the lower wind speeds. GMFs for the mean NRCS (A_0) from the CMOD5.h [10] and OSWT/IWRAP 2016 [11] models where they are valid are shown as solid and dash-dotted lines, respectively. The dashed line at 20° shows the extrapolation from the OSWT/IWRAP 2016 model. Fig. 2 shows the same, except for HH-polarization.

In general, the mean observed NRCS matches the mean modeled wind speeds closely at all incidence angles. Due to the aircraft drift angle, the scatterometer is likely observing

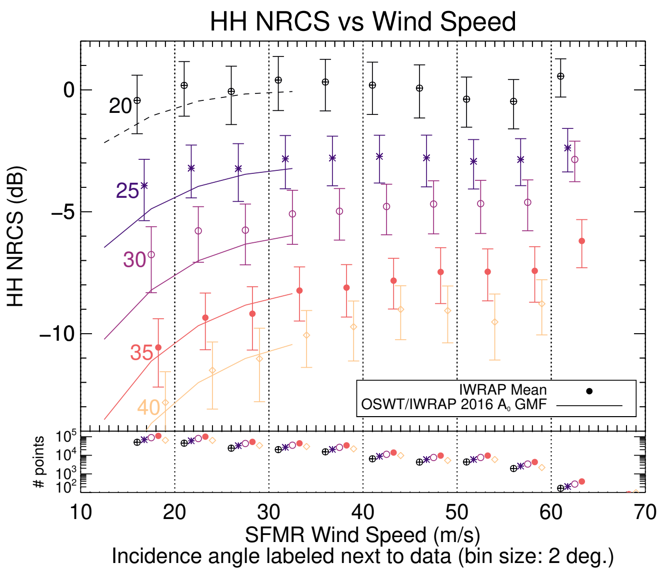

Fig. 2: Co-polarized (HH) NRCS in dB as a function of SFMR wind speed measured in Hurricane Matthew on 1 October 2016. Five sets of averages, each over 2° of incidence angle, are shown in the top panel with number of samples in the bottom panel. Each symbol is shifted slightly for clarity; the actual wind speed value it represents is the center of each wind speed bin. The interquartile standard deviations are shown as vertical bars. Saturation at all incidence angles occurs at high winds.

between upwind and crosswind and between downwind and crosswind relative wind directions for most of the time. Both of these situations are expected to change the NRCS a little above the mean, especially at lower wind speeds.

NRCS saturates at high wind speeds, consistent with earlier observations [8]. We observe the HH-polarized measurements to saturate at lower wind speeds than previously estimated, however.

Fig. 3 shows the cross-polarized (VH) NRCS, corrected for polarization mixing, as a function of surface wind speed. There is a departure from the models, but in the opposite direction of the co-polarized NRCS. Most of the data falls between the 30° and 40° models, albeit 2 dB lower. It is unclear whether this is due to a constant calibration offset or if part of the storm environment is not controlled for properly. However, this does not affect the conclusions that can be drawn based on the relative trend with wind speed. For the wind speeds shown, the VH NRCS do not show signs of saturation. The NRCS measurements are consistent with the observations of [3], given that the data presented here are corrected for polarization mixing and are thus slightly lower.

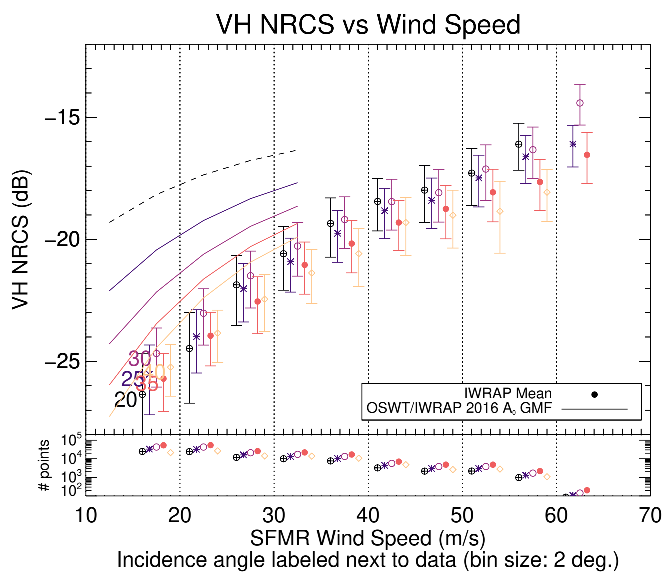

Fig. 3: Cross-polarized (VH) NRCS in dB as a function of SFMR wind speed measured in Hurricane Matthew on 1 October 2016. Five sets of averages, each over 2° of incidence angle, are shown in the top panel with number of samples in the bottom panel. Each symbol is shifted slightly for clarity; the actual wind speed value it represents is the center of each wind speed bin. The interquartile standard deviations are shown as vertical bars. NRCS is assumed to be independent of relative wind direction at these speeds.

4. CONCLUSIONS

The NOAA Hurricane Matthew flight on 1 October 2016 was a unique opportunity to sample high sea-surface wind speeds from an airborne scatterometer for an extended period of time. Consistent with earlier results, we observe saturation of co-polarized NRCS at high winds and no saturation at cross-polarized NRCS. These data suggest that cross-polarized NRCS will be useful for high-wind retrievals by scatterometers when the spatial resolution of the instrument is small enough to properly sample them.

5. ACKNOWLEDGMENT

The authors thank the NOAA/NESDIS Ocean Remote Sensing Program for its support of their flight experiment program; the NOAA Hurricane Hunters and support staff at AOC for their assistance in acquiring these data; and the European Space Agency for loaning the antenna.

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