Comment and discussion on "Scatterometer Hurricane Wind Speed Retrievals using Cross Polarization, by G-J van Zadelhoff et al. "

Paul A. Hwang
Remote Sensing Division, Naval Research Laboratory, Washington DC, USA
paul.hwang@nrl.navy.mil

1. INTRODUCTION

As outlined in my review comments of the original manuscript:

The authors present their analysis of high wind retrieval using cross polarized radar backscattering cross section (VH NRCS). From compiling 19 hurricane hunter missions of SFMR wind measurements with RADARSAT-2 images, they are able to double the wind speed range from previous reports. The relationship between VH NRCS and wind speed deviates significantly from previous formulas for the wind range between 20 and 45 m/s. A new GMF is presented for this wind range. Comparison study with numerical prediction (ECMWF) is also presented.

This is an interesting paper and obviously useful in new scatterometer development. There are only a few minor points I would recommend the authors to clarify in their revision.

(1) The term "**linear**" [between VH NRCS and wind speed] is confusing (e.g., abstract: "The VH backscatter has a linear relationship with respect to wind speed" as well as in many other places in the text). The linear fit is between wind speed and VH NRCS in dB, so the VH NRCS (in physical unit of backscattering cross section) increases exponentially with wind speed. This should be clarified in the paper and the phrase "linear fit" needs to be used carefully.

(2) P9L22: "**One of the conclusions in literature was a lack of apparent incidence angle dependence.**": This statement is inaccurate. The incidence angle dependence is clearly illustrated from theoretical computations (e.g., [Valenzuela 1967 IEEE TAPv15p552;] Hwang et al. 2010; Voronovich and Zavorotny 2011 IGARSSp2033) and earlier analysis of a small RADARSAT-2 dataset (see Hwang et al. 2010, Fig. 4b; Voronovich and Zavorotny 2011 Fig. 2). In fact, the empirical formula of Hwang et al. (2010) incorporates the incidence angle factor (admittedly the result is not very good in high winds as the formula was based on a much smaller dataset). The VH NRCS range as a function of incidence angle shown in the present manuscript (Figs. 3 and 4) are consistent with those reported in the earlier publications.

To stimulate discussion, here I expand on those two comments and extend analysis to the directional distribution since the statement "**…the retrieval of wind direction … is not possible for the VH channel**" (van Zadelhoff et al., 2013, p. 7949) seems to be questionable at best and "**…that the VH versus wind speed shows no dependence to the wind direction angles, as observed by Hwang et al. (2010), …**" (van Zadelhoff et al., 2013, p. 7959) is incorrect. The directional distribution was not discussed in Hwang et al. (2010) "[b]ecause the sample size in each incidence angle bin is relatively small for resolving directional distribution" (p. 4).

With regard to the incidence angle dependence in their published revision, the authors state that "**This** [the incidence angle dependence] **was also indicated by measurements using a limited set of the RADARSAT-2 SCWA data (Hwang et al., 2010). The high signal-to-noise measurements from the fine-quad polarization mode, however, showed a lack of apparent incidence angle dependence (Vachon and Wolfe, 2011; Zhang and Perrie, 2011).**" (p.7954). The data presented in Hwang et al. (2010) are in fact from the fine-quad mode, this was clearly stated in their p. 3 (the first sentence of sec. 3).

I conclude with the suggestion for a more systematic analysis of the incidence angle and azimuthal angle dependences in their next phase of data analysis in order to further improve the retrieval algorithm of wind speed and direction using cross-pol radar backscatter.

2. RELEVANT PROPERTIES OF THE CROSS-POLARIZATION DATA

2.1. Incidence angle dependence

As outlined in Hwang et al. (2010b) [referred to as H10 from here on], the solutions of the co-pol and cross-pol NRCS of a slightly rough patch tilted by the ocean surface have been summarized in Valenzuela (1978). This surface scattering model is called tilted Bragg or composite-surface Bragg scattering model (CB). The detail is given in sec. 2 of H10. The co-pol radar returns from RADARSAT-2 (R2) show very good agreement with the CB model, the cross-pol is several dB higher than the CB computation, as shown in Figs. 3 and 4 of H10, a simplified version is reproduced here as Fig. 1. For θ between 22.5° and 37.5°, the calculated cross-pol difference is about 2 dB. The R2 data with wind speed U_{10}>~5 m/s, thus with higher signal to noise ratio (SNR), show a similar level of difference: for the quad-pol data, the noise level is about -36 dB (Hwang et al., 2010a; Vachon and Wolfe, 2011), the incidence angle dependence becomes especially clear for those data in Fig. 1c with $\sigma_{0HV} \geq$~30 dB. For R2 dual-pol mode, the cross-pol noise is about 5 to 6 dB higher than that of the quad-pol mode but the incidence angle dependence remains quite noticeable (Hwang et al., 2010a, Fig. 2). The lower panels of Figs. 3 and 4 in van Zadelhoff (2013) [referred to as vZ13 from here on] show a very similar range of incidence angle variation in σ_{0HV}.

2.2. Wind speed dependence

As emphasized in H10, the most significant characteristics of σ_{0HV}, as far as wind speed retrieval is concerned, is the increased sensitivity toward high wind and that the available cross-pol data show no saturation in high winds. These are contrasted with the co-pol returns that may saturate at lower incidence angles, as illustrated in the 22.5°data of Fig. 1 and the wind speed sensitivity obviously decreases toward high wind. The much-larger dataset of vZ13 reconfirms those two very desirable properties (increased sensitivity and unsaturation toward high wind). The clarification of the wind speed dependence is especially valuable for improving our understanding of the backscattering mechanisms. This is further explained next.

It is well known that the wind speed sensitivity of the Bragg resonance surface water waves varies with the EM frequency. The ocean surface roughness spectral density can be expressed as a

power-law function $(u_* / c)^{a(k)}$, here u_* is the wind friction velocity, c is the phase speed of the roughness spectral component. The exponent a thus characterizes the wind speed sensitivity. For the microwave frequencies used in scatterometers, the sensitivity decreases from Ku to L band. In a recent study of the ocean surface roughness spectrum in high winds (up to 60 m/s) combining Ku, C and L band geophysical model functions (GMFs), Hwang et al. (2013) discover that the exponent of the power-law wind speed dependence of the Bragg resonance waves in those three frequency bands converges to 0.75 in high winds (u_* / c >3, or reference wind speed U_{10} greater than about 17 m/s for C band, note c has a minimum value of 0.23 m/s). For comparison, in mild to moderate wind speed the wind speed exponent is about 2 to 2.5 for Ku band, 1.2 to 1.5 for C band and 0.5 for L band (Fig.3 in Hwang et al., 2013). The dataset in vZ13 extends to 40 m/s wind speed and is of great interest.

Figure 2 reproduces the VH GMF of vZ13:

$$\sigma_{0VH}\,(dB) = \begin{cases} 0.592U_{10} - 35.60, & U_{10} \le U_t \\ 0.218U_{10} - 29.07, & U_{10} > U_t \end{cases}. \qquad (1)$$

The transition wind speed U_t suggested by vZ13 is 21 m/s and the resulting curve has an obvious discontinuity (the green curve in Fig. 2a). The discontinuity is eliminated when the matching wind velocity of the two branches U_t=17.46 m/s is used (the blue solid curve in Fig. 2). The information of wind speed exponent can be better detected in a log-log plot. As illustrated in Fig. 2b, the cross-pol response to wind speed can be roughly divided into 4 different wind speed regions: (A) U_{10}<4 m/s, the wind retrieval quality is low because of low SNR. The relatively-high background noise can be caused by sensor hardware as well as environmental factors such as swell and background turbulence contributing to ocean surface roughness that cannot be attributed to wind waves. (B) 4≤ U_{10}<10 m/s, the SNR improves. The wind speed response is more or less linear, suggesting that the surface scattering as described in the CB model dominates the backscatter. As stated in the previous paragraph, for C band the CB model predicts wind speed exponent between about 1.2 and 1.5. (C) 10≤ U_{10}<18 m/s, the cross-pol wind speed response is about quadratic, which is stronger than that of the Bragg waves. The enhanced wind speed sensitivity signifies the increasing influence of non-Bragg contributions attributable to wave breaking, which is expected to depend on wind speed cubed (e.g., Phillips 1985, 1988; Hwang 2009). (D) U_{10}≥18 m/s, the wind speed exponent is about 1.5, which is twice of the C band Bragg wave wind speed exponent in high wind (0.75, see last paragraph) and again indicates the strong non-Bragg contribution of surface wave breaking.

2.3. Azimuthal angle dependence

As mentioned in the Introduction, the directional distribution was not discussed in H10 because the sample size in each incidence angle bin is relatively small for resolving directional distribution (H10, p4), and it is not accurate to state that "It is observed in the plot that the VH versus wind speed shows no dependence to the wind direction angles, as observed by Hwang et al. (2010), …" (vZ13, p.7959).

Here I present the directional analysis from those relatively small samples. Fig. 3 shows the results for the 20°-25° incidence angle bin and Fig. 4 shows the corresponding results for the 30°-35°

incidence angle bin. The quad-pol data are on the left column and the dual-pol on the right. The vertical span of each plotting panel is identical (8 dB). It is evident that the directional signal of cross-pol is as strong as or even stronger than those of the co-pols when SNR is good (quad-pol). Although the cross-pol noise in the dual-pol product is about 5 to 6 dB higher than that of quad-pol, the cross-pol directional signature in the dual-pol product remains significant.

From the point of view of scattering mechanisms, if surface effects dominate, then the cross section (both co-pol and cross-pol) reflects the directional distribution of the ocean surface roughness. Wave breaking also has strongly upwind-downwind asymmetry and will also contribute to cross-pol azimuthal angle dependence in high winds. The authors correctly pointed out that L band cross-pol shows distinctive directional dependence (Yueh et al., 2010). The side-by-side comparison shown in Figs. 3 and 4 clearly indicates that the directional distributions of co-pol and cross-pol are comparable in C band as well for good SNR data.

3. CONCLUDING REMARKS

The analysis reported in vZ13 represents a significant progress on the potential of cross-pol for scatterometer applications, building upon the foundation of H10, Vachon and Wolfe (2011) and Zhang et al. (2011). H10 emphasizes the significance of unsaturation of cross-pol returns in high winds for ocean surface wind retrieval applications and foresees its contribution in future space monitoring of damaging storms such as hurricanes. The analysis of vZ13 confirms that prediction. The cross-pol wind retrieval algorithm presented in vZ13 makes use of the backscatter intensity alone. In an accompanying paper (Belmont Rivas, Stoffelen and van Zadelhoff, 2013), the authors show that the addition of a single VH capability in the mid beam of an ASCAT-type scatterometer improves the determination of wind speed over the entire scatterometer swath, with wind speed RMS errors of about 0.5 m/s.

There are clear incidence angle and azimuthal angle dependences in the cross-pol return. The incidence angle signal is relatively weak: about 2 dB between 22.5° and 37.5°. The directional signal, on the other hand, is as strong as that of the co-pol returns (Figs. 3 and 4). Because of the weak cross-pol return, instrument noise may compromise the directional signal somewhat but its presence remains detectable. It is wonderful that retrieval of high wind speed using cross-pol achieves better results than using co-pols without making use of the directional or incidence angle dependence, but it is incorrect to state that the cross-pol signals do not vary with incidence angle or azimuthal angle. It would be a mistake to write off C-band cross-pol as incapable of wind direction retrieval. Ultimately, the unequivocal determination of the cross-pol directional distribution may require a circle flight or circular scanning experiment similar to that performed by Yueh et al. (2010). In the meantime, side-by-side comparison as shown in Figs. 3 and 4 suggests very similar directional distributions between co-pol and cross-pol backscatters, and the co-pol directional distribution can be “borrowed” for cross-pol algorithm development. The incidence angle and azimuthal angle dependences can and should be explored to further enhance the performance of cross-pol wind vector retrieval.

4. REFERENCES

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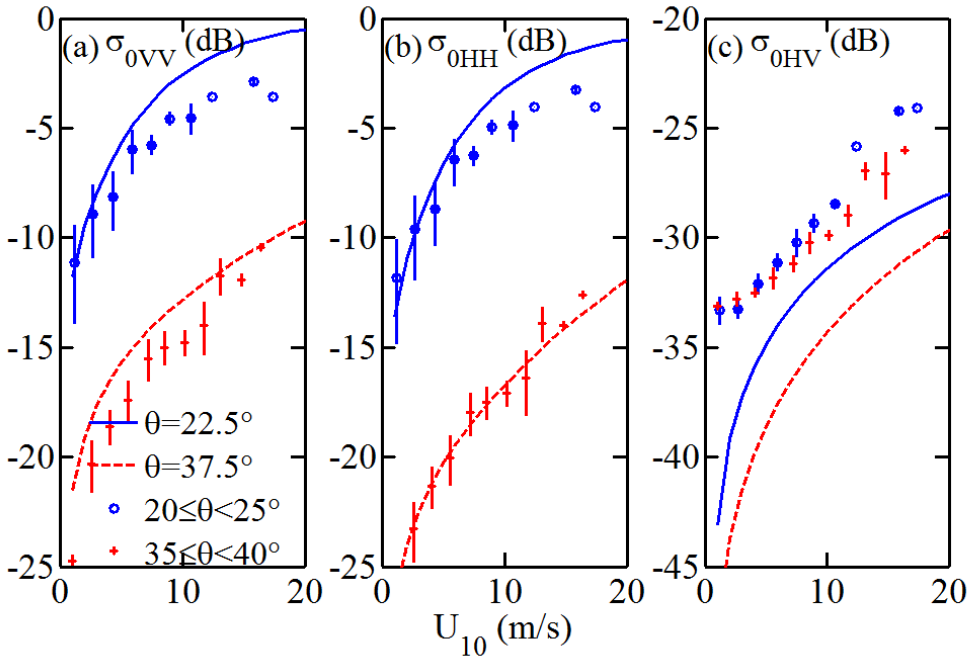

Fig. 1. Comparison of R2 quad-pol backscatters with composite-surface Bragg resonance model [adopted from Hwang et al. (2010b)].

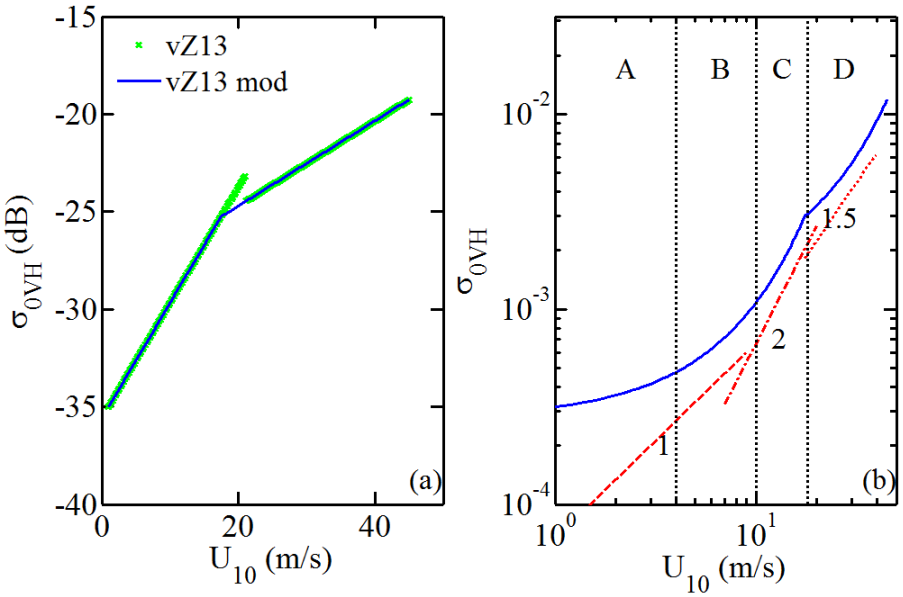

Fig. 2. Investigation of wind speed dependence based on the cross-pol GMF of van Zadelhoff et al. (2013). A modification of the transition wind speed at 17.4 (from 21) m/s is suggested for maintaining continuity.

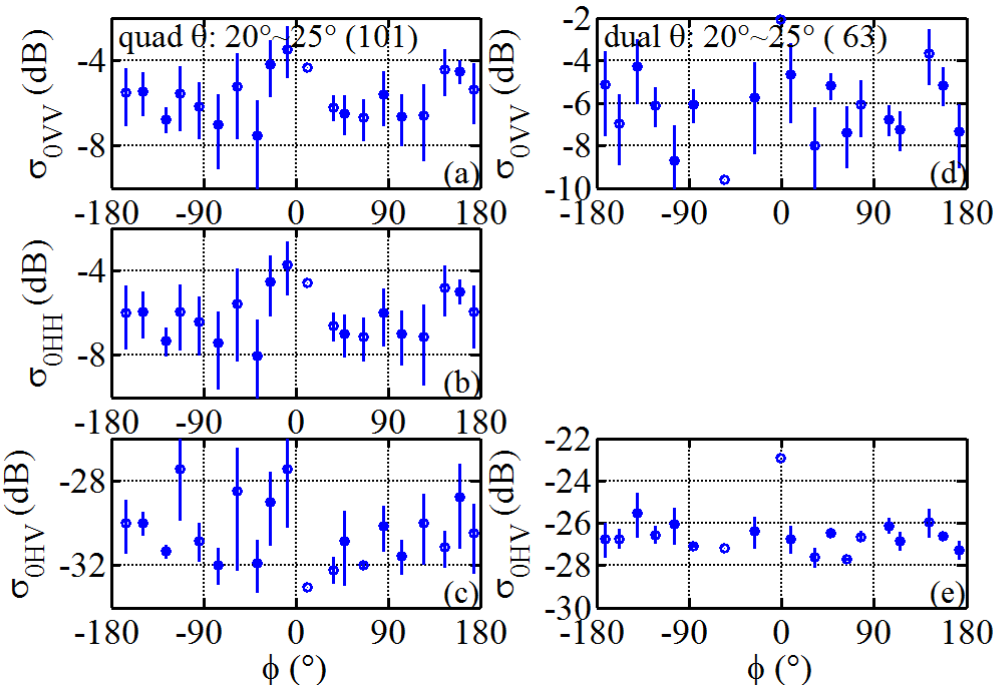

Fig. 3. Directional distribution of co-pol and cross-pol radar backscatters. Left column shows the R2 quad-pol results and the right column shows the dual-pol results. Incidence angle between 20° and 25°. The sample size is shown in parentheses of the top panels.

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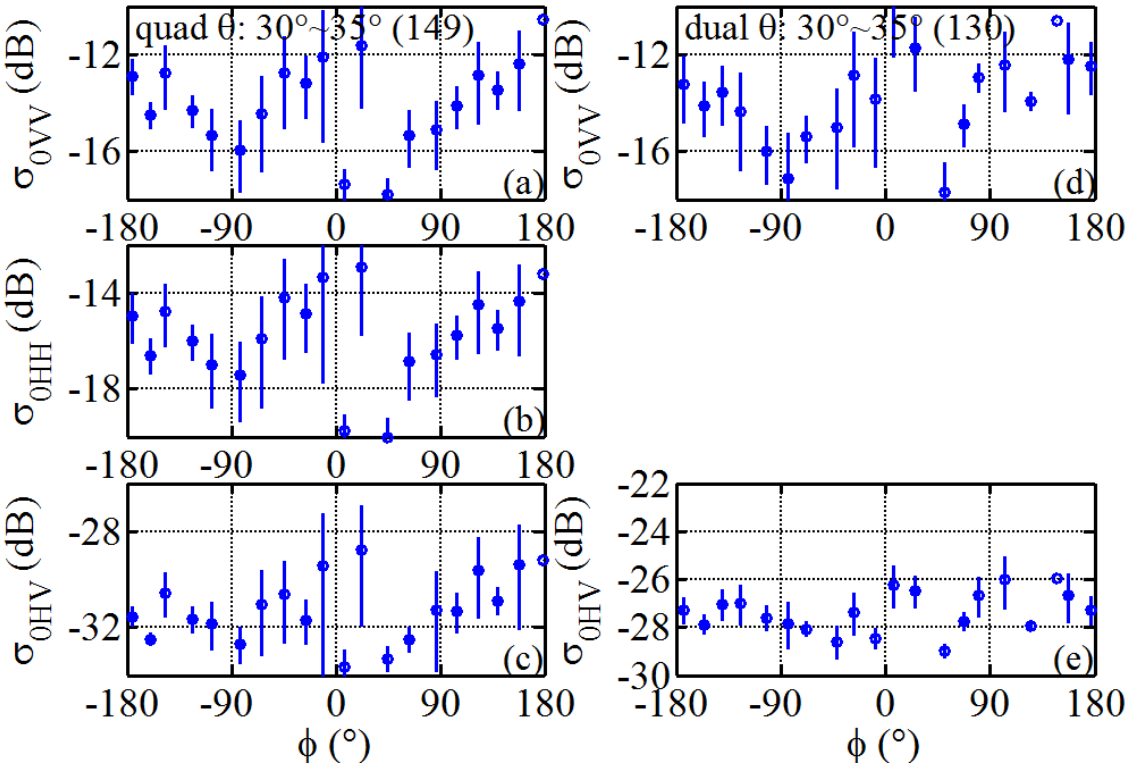

Fig. 4. Same as Fig. 3 but incidence angle between 30° and 35°.

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