Response to the review comments by Paul A. Hwang

Gerd-Jan van Zadelhoff, A Stoffelen, P. W. Vachon, J. Wolfe, J. Horstmann, and M. Belmonte Rivas

We thank the referee for making his thorough and useful review of our paper, especially the initiation of the discussion was useful since it enforced us to re-evaluate the methodology of our approach. Below we start with a point by point response to the review comments and end with the discussion as initiated by the reviewer. When referring to the original manuscript (amtd-2013-139) the abbreviation van Zadelhoff et al. 2013 is used, the abbreviation Hwang 2013 is used for the comments made by Paul A. Hwang (amtd-6-C2376-2013-supplement).

1 Minor issues

Comment 1: Hwang 2013 Line 22: We agree with the referee on his comment that the use of the word linear in this way is confusing. As the entire manuscript dealt with VH in dB, we implicitly assumed that this would be clear. This is, however not the case and we made changes to the text at a number of places. In a number of cases we included the use of dB when a linear relationship was discussed and in four cases remarked that the signal itself shows an exponential relationship with respect to wind speed.

Comment 2: Hwang 2013 Line 28:
The referee is correct with his remark. The statement in the manuscript was a remark based on the results from the high signal-to-noise measurements from the quad-pol beam, where no dependence was visible, and did not take into account the theoretical efforts in this field. We have altered this part of the text, including the theoretical work from the two papers mentioned in the comment.

Start of the discussion: As will be shown in more detail below, we have performed three additional tests of the data, including one similar to the referee his Figure 3 (Hwang 2013). Based on the data available to us we cannot detect a wind direction dependence in the data. However, since the error estimates in the VH signal distribution are relatively large we will rephrase comments, regarding the (im)possibility of retrieving wind direction with the VH signals, by taking into account the uncertainties.

You are right that the wind direction dependence was not discussed in Hwang 2010. The sentence will be deleted. In the discussion of the incidence angle dependence : Hwang 2013 Line 46, the use of the SCWA data referred to the GRL paper from the same year : Hwang, P. A., B. Zhang, and W. Perrie (2010), Depolarized radar return for breaking wave measurement and hurricane wind retrieval, *Geophys. Res. Lett.*, *37*, L01604, doi:10.1029/2009GL041780., where results from both the quad and dual pol were presented. The remark in the manuscript combined the observations/discussion from both papers in to one sentence. This sentence will be rephrased to be more clear/correct.

2 Discussion

2.1 Checking images

The cross-polarization (VH) images have a low signal strength in comparison to the more generally used co-polarization (VV) signals. In the paper we show that we were not able to retrieve directional information using a statistical analysis. In the comments from Hwang 2013 a different method of looking at the statistics was used and we will follow his approach within this discussion. However, before combining all wind speed data to a single value, first, a visual inspection of the data is performed by comparing incidence angle corrected VV and VH signals. In the paper (van Zadelhoff et al. 2013) images of the direct measurements are shown in Figure 1, with the well defined Hurricane eye in the VH-image and the clearly apparent incidence angle dependence in the VV-image. The VH-image can be made incidence-angle independent assuming the relationship 5 in van Zadelhoff et al 2013. Strictly speaking this relationship can only be retrieved below 20m/s due to the lower statistics in the >20m/s regime, however in the images below we assume that the same relationship is valid for the entire wind speed regime. In case of the VV-signals the incidence-angle dependence has to come from the CMOD5n (Hersbach 2009) relationship valid for these signals. The CMOD5n dependence is described by the top equation in Eq 1.1 , with B_0, B_1 and B_2 depending on both the incidence angle and wind speed. The φ symbol describes the wind direction angle with respect to the instrument viewing direction.

$$
\begin{aligned}
VV &= B_0 \cdot (1 + B_1 \cos\varphi + B_2 \cos 2\varphi)^{\eta} \\
B_0 &= b_{00}(\theta) \cdot b_{01}(\theta, u_{10}) \qquad (1.1) \\
VV_{35} &= VV / b_{00}(\theta) \cdot b_{00}(35^{o})
\end{aligned}
$$

The B_0 parameter can be separated into two parts, one depending on the incidence angle only (b_{00}) and one depending on both the incidence angle and the wind speed (b_{01}). The most important incidence angle dependence within the function is described by b_{00}, with b_{01} providing a minor correction on this. Using the b_{00} parameter the VV image is made incidence angle independent (VV_{35}) by mapping all signals to an incidence angle of 35 degrees, similar to the VH_{35} relationship defined in the manuscript. In Figure 1, images are shown for four individual Hurricanes in both VH_{35} and VV_{35}. In all cases ,the VH_{35} signals (top panels) show no preferred wind direction. In the VV_{35} signals (bottom panels) however, the well known feature visible in scatterometer data (e.g. ASCAT) shows up, with higher signals for winds approaching or along wind with respect to the instrument viewing direction and lower signals for cross winds.

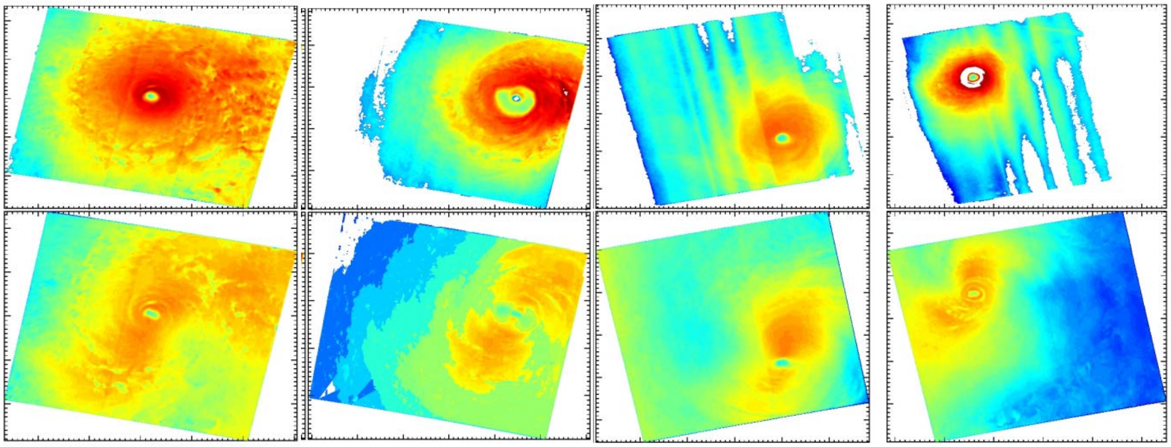

Figure 1: Example of the VH_{35} (top) and VV_{35}(bottom) incidence angle corrected signals for four Hurricane images. The VV_{35} signals show a strong directional dependence of up & down wind versus cross wind, whereas the VH_{35} signals have no visible azimuth dependence.

Based on this Figure, the VH signal strength can only suffer from a relatively weak wind direction dependence, if any. There is at least no preferred signal strength for up-wind in comparison to the cross wind directions. Even though our eyes are very sensitive in detecting patterns, these images provide only circumstantial evidence on a wind direction dependence for the VH channel.

2.2 Corrections to the used statistical approach

Based on the removed incidence angle dependence (Section 2.1), Figure 7b of the manuscript under discussion can be redrawn. In Figure 2 the newly made VV-panel is depicted, showing the VV wind direction dependence in color shading by calculating the median signals within a wind-direction, wind-speed cell. Instead of the incoherent Figure 7b panel, due to the incidence angle dependence in the VV measurements, the VV_{35} measurements show the expected signal strength versus wind direction with high signals at 0 and 180 degrees and low signals at 90 and 270 degrees for all wind speeds between 10 and 30 m/s.

The VH signals do not depict the same wind direction behavior (top panel). There seems to be a decrease of signal strength at 90^o, e.g. note the yellow color between 40 and 150 degrees, but this is not accompanied by a similar behavior at 270^o. This does therefore not show a similar behavior as seen in the VV signals. Also, when using the second wind direction as an input, rotation around the Hurricane center, the small peak at 90^o is smoothed away, suggesting that this was an artifact within the data, whereas the VV image remains the same as shown below.

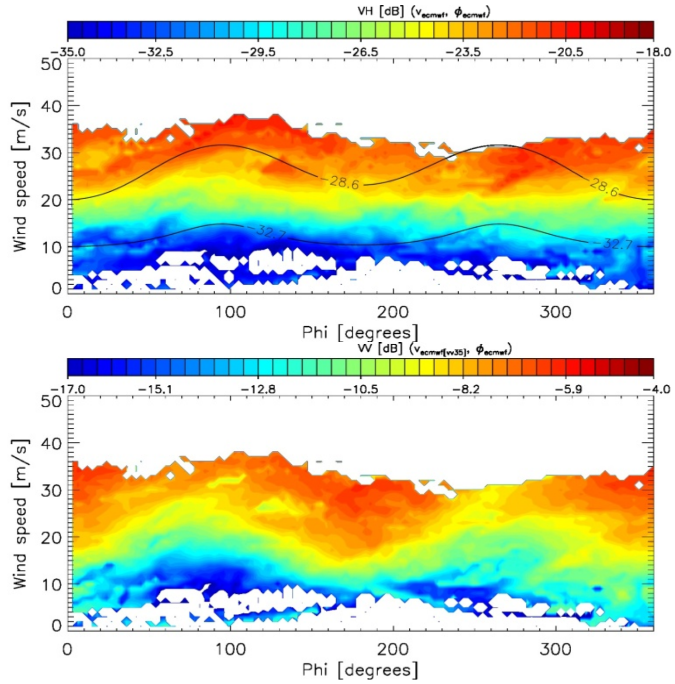

Figure 2: Joint distributions of the median signal strength versus ECMWF wind velocities and the wind direction angle for the combined 19 hurricane images. The color scale depicts the median incidence-angle corrected VH or VV at each position. In the top panel the wind direction dependence of the VH signals vs. wind speed is shown, indicating the lack of wind direction dependence in the VH channel. The solid black lines were derived from L-band cross polarization signals (Yueh et al., 2010), which do depend on the wind direction. The bottom panel shows the same plot but color coding the VV signal. The VV signals have been made incidence angle independent and show the well described wind direction dependence of lower signals at cross wind directions (90^{o} & 270^{o}) versus higher signals at up- and down-wind directions (0^{o} and 180^{o}).

The figures under discussion Hwang 2013 Fig3 & Fig4 can be created by collapsing the wind speed dependence shown in Figure 2, thereby trying to increase the precision of the retrieved wind direction dependence. As a counter argument this also increase the uncertainty in the signals as the signal strength depends exponentially on the wind speed.

In Figure 3 the Hwang 2013 Fig4 is created using the RadarSAT-2 Hurricane dataset, collocated with the wind direction. Both wind direction estimates discussed in the paper are used, e.g. the wind direction from the ECMWF forecasts (φ_{ecmwf}) and the wind direction assuming perfect rotation around each Hurricane center (φ_{rot}). The left panels shows the number density distribution for the VH and VV signal, with the local mean value and its 1σ standard deviation overplotted, for all wind speeds between 5 and 20m/s with an incidence angle dependence between 30 and 35 degrees. The right panels depicts the median values against both the wind direction regimes. The right bottom panel shows the expected result for the VV channel, a high signal strength at 0 and 180 degrees and low signal strength at the cross directions (90 and 270 degrees). This plot also shows that both wind direction methods provide, in general, accurate descriptions of the actual wind direction. The VH median results do not show a clear wind direction dependence. The number density distributions of the VV measurements follow the same pattern as its median results, the VH number density distribution is spread out over a larger range of signal strength, resulting in the larger error estimates around the median signal strength. In the shown

VH distribution any variation in the median seems to depend more on the available data at each location, i.e. the positions of the different Hurricanes within the images, as is for instance shown by the two arcs in between 170 and 280 degrees.

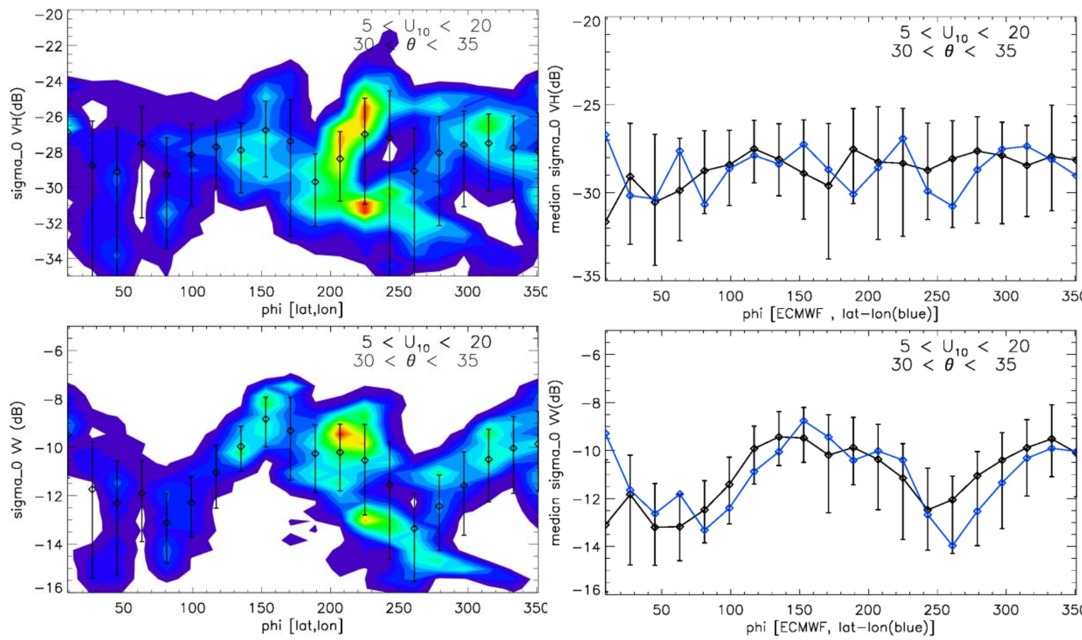

Figure 3: Number density distributions of the available VH(top panels) and VV(bottom panels) signals versus wind direction. The left two panels use the φ_{rot} wind direction, with the diamonds indicating the mean value and 1σ error within a 20 degrees wind direction bin. In the left two panels the median values are over plotted for the φ_{ecmwf}(black) and φ_{rot}(blue) distributions. The 1σ error estimates for the φ_{ecmwf} distribution is added for an estimate of the uncertainty. Note that, especially in the case of the VH measurements, the distributions are not Gaussian in sigma_0 and the error estimates are only indications of the true error estimates.

2.3 Conclusions

Based on the available observation of 19 Hurricane images measured by RadarSAT2, no wind direction dependence is visible. The images in Figure 1 depict a clear dipole within the incidence angle corrected VV-signals, whereas in the case of the VH signals no pattern is visible. In Figure 2, the incidence angle corrected VV signals show that at different wind speeds the signal strength is strongest when measuring along the wind direction and lowest when measuring across the winds. The VH signals do show some variation at the different wind speeds but these are not consistent harmonics. Finally when combining all the data with wind speeds in between 5 and 20 m/s the VV signals again show the expected wind direction dependence, both in median but also in its number density distribution. The number density distribution in the VH channels spread out more evenly over a larger signal strength regime resulting in a near constant median signal strength for all wind directions. However, this more evenly spread out distribution also results in larger standard deviations for the distribution.

Based on the discussion presented above we intend to alter the paper in the following ways. First Figure 7 of the paper will be adjusted. We propose to change the second panel into the lower panel of Figure 2 presented above. The third panel of Figure 7 is changed in to the top right panel of Figure 3, to show the median results when combining all available data. The text will be altered in order to describe the changes in Figure 7. In the paper we now present the lack of wind direction dependence very strictly. Since the width of the distributions are especially large for the VH signals due to noise this will be reflected in the discussion more evenly.