The benefit of HH and VH polarization in retrieving extreme wind speeds for an ASCAT-type scatterometer

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Abstract—The wind retrieval performance of a fixed fan-beam scatterometer operating at C-band in VV polarization (ASCAT-type) is well established in the range of 0-25 m/s. This work evaluates prospective extensions with HH and VH polarized beams aimed at improving retrievals at extreme wind speeds, from 25 to 65 m/s. The Geophysical Model Functions (GMFs) for C-band VV, HH and VH polarized backscatter used in the wind retrieval simulations are defined, along with an objective assessment of the quality scores ascribed to the optional beam configurations. Our study finds that the introduction of a VH capability in the mid beam improves the determination of wind speed over the entire scatterometer swath, with wind speed RMS errors of about 0.5 m/s. The introduction of HH beams in the fore/aft antennas improves the determination of the ocean surface wind vector (wind speed and direction) but over a more limited portion of the outer swath, with wind vector RMS errors as low as 6 m/s, but conditioned to a priori information to resolve the directional ambiguity. If the determination of wind speed prunes over the determination of wind vectors at high wind speeds, then the introduction of a single VH capability in the mid-beam antenna comes forth as the most simple and cost-effective manner to extend the wind retrieval capabilities of an ASCAT-type scatterometer into the domain of extreme winds.

Index Terms—Satellites, antennas, polarization, sea surface electromagnetic scattering, sea measurements, wind.

I. INTRODUCTION

Wind retrieval from the European Polar System Second Generation (EPS-SG) satellite scatterometer is anticipated to be one of the main Numerical Weather Prediction Satellite Application Facility (NWP SAF) products in the 2020 time frame. The reference EPS-SG scatterometer design is a C-band (5.3 GHz) fixed fan-beam configuration with six antennas that transmit and receive vertical polarization (VV) over a range of incidence angles of 20-65 degrees [1]. This follows the design of the ASCAT instrument on MetOp which operates in VV polarization and has established excellent quality winds in the dynamic wind range of 4-25 m/s. For EPS-SG, an innovation is foreseen that adopts alternate polarization options to achieve breakthrough performance at extreme winds. Simulations of wind retrieval performance have been used to 1) consolidate a simplified reference EPS-SG scatterometer design with only VV polarization and 2) support decisions on optional system requirements regarding wind retrieval skills at extreme winds. In this paper, the addition of VH and HH polarization capabilities to the reference VV beams is considered for wind speeds up to 65 m/s.

Section II presents the methodology employed to evaluate the introduction of HH and VH polarized beams, which relies on wind retrieval simulations at different wind speed, direction, and cross-track locations. Section II.A describes the empirical Geophysical Model Functions (GMFs) at C-band for VV, HH and VH polarized backscatter used to simulate the ocean surface measurements. These GMFs determine the sensitivity of each beam configuration to the wind vector. Section II.B provides a brief description of the end-to-end performance simulator used to test different configurations under realistic instrumental noise conditions. Section II.C describes the figures of merit used to evaluate the quality of the wind retrieval, which is as affected by instrumental noise as by GMF non-linearities. Section III discusses the merits of the two best alternate beam configurations in relation to the reference scatterometer concept, followed by a summary with recommendations presented in Section IV.

II. METHODOLOGY

A. Geophysical Model Functions

The geophysical model function (GMF) is an empirically derived function that relates microwave backscatter to the ocean surface wind vector (equivalent neutral wind speed at 10-m height $U_{10N}$ and wind direction $\phi$) and scatterometer beam geometry (incidence angle $\theta$ and azimuth angle $\phi'$) in the form of $\sigma^0 = \text{GMF}(U_{10N}, \theta, \phi - \phi')$. It is usually derived on the grounds of a comparison between actual backscatter measurements and a reference ocean surface vector wind derived from independent observations or model analyses. For
the purpose of this work, the domain of validity of the GMFs must be defined for the entire incidence angle and dynamic wind range of the EPS-SG scatterometer (from 20 to 65 degrees and up to 65 m/s).

1) VV polarization

The GMF for vertically polarized ocean backscatter, denoted CMOD5.N, was determined on the basis of a comparison between ERS-2 AMI (Active Microwave Instrument on European Remote Sensing Satellite) backscatter and collocated ECMWF (European Center for Medium-range Weather Forecasts) first-guess winds ([2], [3]). For winds larger than 25 m/s, the experimental findings of [4] were used as guideline. The collocated data was stratified according to incidence angle $\theta$ and equivalent neutral wind speed $U_{10N}$, and the dependence of VV backscatter, $\sigma_{VV}^0$, on wind direction $\phi$ modeled as:

$$\sigma_{VV}^0(\theta, U_{10N}, \phi) = B_0(\theta, U_{10N}) \cdot \left[1 + B_1(\theta, U_{10N}) \cos \phi + B_2(\theta, U_{10N}) \cos 2\phi\right]^p$$  \hspace{1cm} (1)

where $\phi$ is the wind direction relative to the antenna beam. The $B_0$ term describes the azimuthally isotropic backscatter response for a given wind speed, while the $B_1$ and $B_2$ terms describe the amplitude of the upwind-downwind and upwind-crosswind modulations respectively. The complete functional form of CMOD5.N is given in [5]. The general agreement between the CMOD5.N and the high wind speed IWRAP VV polarization model [6] is verified in Fig. 1 and considered satisfactory up to wind speeds of 65 m/s, with maximum departures below 1.5 dB in upwind conditions.

Note that VV polarized backscatter from the ocean surface saturates above a wind speed of 25-30 m/s, that is, it becomes insensitive to changes in wind speed and wind direction. Saturation leads to misestimation of extreme winds, and errors in storm prediction and weather warnings.

2) HH polarization

The GMF for horizontally polarized ocean backscatter is obtained through incorporation of a model of the ocean co-polarization ratio (CPR) as:

$$\sigma_{HH}^0(\theta, U_{10N}, \phi) = (1/CPR) \cdot \sigma_{VV}^0(\theta, U_{10N}, \phi)$$  \hspace{1cm} (2)

where $\sigma_{VV}^0$ is the CMOD5.N model defined previously. Based on available empirical data and a reasonable use of physically based upper and lower bounds [5], the ocean CPR model is defined as:

$$CPR = \sigma_{VV}^0(\theta, U_{10N}, \phi)/\sigma_{HH}^0(\theta, U_{10N}, \phi)$$  \hspace{1cm} (3)

using a combination of VV to HH co-polarization ratios from the airborne STORM dataset at low winds and low incidences [7], which is independent of wind speed, and the airborne IWRAP dataset at high winds and large incidences [6], as illustrated in Fig. 3. The behavior of the ocean CPR model is interpolated between the STORM and IWRAP dataset domains and extrapolated into the 50 to 65 degrees range of incidence angle based on the IWRAP dataset. The complete functional form of ocean CPR is given in [5]. Shown in Fig.2, the ocean HH-polarized backscatter is in general weaker than VV, but more sensitive to high wind speeds at large incidence angles (above 40 degrees). At lower incidences, the ocean CPR approaches unity so that HH and VV backscatter behave much alike.

3) VH polarization

The GMF for cross-polarized VH ocean backscatter at C-band has been described by [8] and [9] using cross-polarized RADARSAT-2 data. These studies suggest that VH backscatter depends very weakly on incidence angle and wind
direction, showing no signs of saturation at low-to-moderate wind speeds. A simple formulation, valid for incidence angles from 20 to 50 degrees and wind speeds from 0 to 20 m/s, is given by [9]:

$$\sigma_{0, VH}^0(U_{10}) = 0.592 \cdot U_{10} - 35.6 \quad U_{10} < 20 m/s \quad (4)$$

For wind speeds above 20 m/s, the functional form of the GMF for VH polarized backscatter has been examined by [10]. Its empirical basis includes RADARSAT-2 VH and VV backscatter measurements collected at 20 to 50 degrees of incidence, collocated against SFMR (Stepped Frequency Microwave Radiometer) winds [11] and ECMWF analyses over tropical hurricane conditions (up to 50 m/s). At extreme winds, the VH GMF can be written as a function of wind speed as:

$$\sigma_{0, VH}^0(U_{10}) = 0.218 \cdot U_{10} - 29.1 \quad U_{10} > 20 m/s \quad (5)$$

The final VH GMF composite is formed letting (4) and (5) transition around 20 m/s, as shown in Fig. 4. In general, the ocean VH response is much weaker than either HH or VV returns, with exception of crosswind HH conditions at large incidence angles. Also note that the VH GMF is considered insensitive to incidence or azimuth angle, so its performance is expected to be uniform across the instrument swath and flat across wind directions.

B. End-to-end performance simulator

Our performance assessment methodology rests on the output wind statistics produced by the end-to-end wind retrieval simulator shown schematically in Fig. 5 [1]. The end-to-end wind retrieval simulator converts an input wind vector (\(v_{IN}\)) into a vector of error/noise-free backscatter measurements using the GMFs defined above and sampled at observation angles specified by the scatterometer observation geometry as a function of cross-track location. Random noise is added to the backscatter coefficients according to specified instrumental noise levels and the result is injected to the retrieval core of the simulator to generate an output wind vector (\(v_{OUT}\)). The retrieval yields the wind state that lies closest to the observation vector in the measurement space. System noise includes instrumental (detector plus fading, Kp) and geophysical noise, the latter considered relevant at low winds only [12]. We assume that the system noise for all polarization modes is identical to the reference VV case, which guarantees a Kp of 3% for backscatter larger than -25 dB with a gradual 3 to 10% increase from -25 to -40 dB. After a large number of retrievals with different noise realizations (~1000 per input wind and cross-track location), the wind solutions are collected and binned into output wind probability arrays, called \(P_{\text{obs}}(v_{OUT}|v_{IN},WVC)\) and shown in Fig. 5, which describe the dispersion of wind solutions \(v_{OUT}\) about the true wind \(v_{IN}\) for a given cross-track location WVC (wind vector cell). The output wind probability arrays allow the characterization of the retrieval error via mean statistics such as the wind vector root-mean-square (RMS) error, the wind vector bias or the presence of multiple ambiguous solutions [13].

C. Figures of merit

At low-to-moderate winds, the output wind probability arrays of an ASCAT-type scatterometer generally show a tight primary maximum centered on the true wind with a weaker secondary maximum 180 degrees apart (see Fig. 5). Under these conditions, it is possible to isolate the primary maximum using some a priori information about wind direction, e.g. from a NWP (Numerical Weather Prediction) model analysis, and proceed to calculate an ambiguity resolved wind vector RMS (VRMS) as:

![Composite C-band VH backscatter model as a function of wind speed, showing a transition around 20 m/s between moderate and extreme wind sensitivities.](image)
where the a priori NWP wind condition $P_{\text{NWP}}(V_{\text{out}} - V_{\text{in}})$ is a Gaussian function centered about the true wind with a certain standard deviation. The NWP prior provides the context in which the instrument data is used in practice. It prevents penalizing ambiguities that are easily identified and removed as erroneous winds. The Gaussian shape is a reasonable assumption for uncertainty in the wind components $u$ and $v$, and a rather conservative value of the standard deviation has been chosen (one-dimensional $\sigma_{\text{NWP}}$ of 3.2 m/s for $U_{10} < 20$ m/s and $\sigma_{\text{NWP}}$ of 10 m/s for $U_{10} > 20$ m/s) to make sure that the scatterometer helps when the prior is relatively poor, generally in dynamical conditions. An extreme wind event such as a hurricane is most challenging for a global or regional NWP model and therefore further inflation of the NWP prior seemed appropriate. At higher winds, the distinction between the primary and secondary maxima becomes less clear as the azimuthal signature in backscatter produced by wind direction flattens by saturation, with the B1 and B2 terms in (1) approaching zero. In consequence, the output wind probability arrays at extreme winds start becoming annular (see Fig. 11) and the ambiguity resolution no longer a matter of choosing between two tightly packed peaks 180 degrees apart, but one where wind solutions become strongly constrained by a priori NWP information, as VRMS approximates $\sigma_{\text{NWP}}$. When wind vectors become strongly constrained by a priori information, the VRMS metric ceases to be useful and a new performance metric becomes appropriate. In this case, a wind speed RMS (WSRMS) figure of merit that solely focuses on wind magnitude may be introduced as:

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\text{WSRMS}(\vec{v}_{\text{true}}, \text{WVC}) = \left( \int \left( \vec{v} - \vec{v}_{\text{true}} \right)^2 P_{\text{obs}}(\vec{v} | \vec{v}_{\text{true}}, \text{WVC}) d^2\vec{v} \right)^{1/2}
\]

For testing the introduction of HH and VH capabilities to the reference EPS-SG scatterometer concept, preliminary simulations are carried out for the following beam configurations (see Fig. 6):
Because the EPS-SG scatterometer design can accommodate both VV and VH beams simultaneously in transmit/receive, but not VV and HH, the VH capability is added to the reference VV beam, while HH capabilities replace VV beams where indicated. The resulting VRMS and WSRMS performance scores at different input wind speeds are shown in Figs. 7 and 8 as a function of cross-track location in the swath.

In the nominal wind speed range ($U_{10N} < 25$ m/s), there are three configurations that perform worse than the reference VV-only design, which motivates their disqualification. The VH configurations A and B have worse VRMS scores over outer swath locations because of convergence problems with the azimuthally isotropic VH components (at this point, the wind inversion cost function is suboptimal [14] as distances in the measurement space are not optimized via noise-weighting factors). The HH configuration D (all HH beams) has worse WSRMS scores in this range, because of weaker HH signal levels at low winds.

At higher wind speeds ($U_{10N} > 25$ m/s), the strengths of the HH and VH polarization families relative to VV backscatter begin to be noticed. The HH GMF is characterized by enhanced sensitivity to high wind speeds at high incidence angles, so that configurations that hold the HH beams at higher incidences (configurations D and E with HH on the fore and aft beams) show better VRMS scores at extreme

![Fig. 7. Performance VRMS scores (scaled by $\sqrt{2\sigma_{NWP}}$) for all beam configurations at 10 m/s (left), 45 m/s (mid) and 65 m/s (right)](image)

![Fig. 8. Performance WSRMS scores for all beam configurations at 10 m/s (left), 45 m/s (mid) and 65 m/s (right)](image)

![Fig. 9. Performance VRMS scores (scaled by $\sqrt{2\sigma_{NWP}}$) for the two best beam configurations at 10 m/s (left), 45 m/s (mid) and 65 m/s (right)](image)

![Fig. 10. Performance WSRMS scores for the two best beam configurations at 10 m/s (left), 45 m/s (mid) and 65 m/s (right)](image)
winds over outer swath cells (see Fig.7). We note that adding a single HH beam to the reference design (configuration F) leads to a performance worse than baseline, most likely because of nonlinearities that do not compensate for potential side benefits. Because VH information does not carry any sensitivity to wind direction, the improvement in adding a VH capability is primarily felt in WSRMS scores (see Fig.8), and this improvement is relatively insensitive to the number of VH channels involved.

These considerations, along with a reasonable sense of economy, should lead us to the two best alternate beam configurations to augment the wind retrieval skills of the reference EPS-SG scatterometer at extreme wind speeds, while conserving the wind retrieval quality in the nominal wind range: configuration E (reference VV with HH on fore/aft beams) and configuration C (reference VV with VH on the mid beam). Figures 9 and 10 take a closer look at their performance scores relative to the reference VV concept. Note that a) the wind retrieval quality at 10 m/s, in terms of both VRMS and WSRMS scores, is the same for all three configurations, b) the introduction of HH beams in the fore/aft antennas affords an improved determination of the wind vector at extreme winds just over outer swath cells (see Fig.9) while c) the introduction of a VH capability in the mid beam brings an improved determination of wind speed over the entire swath at extreme winds (see Fig. 10).

We may illustrate these differences further by taking a closer look at the output wind probability arrays for specific wind conditions. Figure 11 shows the distributions of wind solutions observed by the different beam configurations (VV baseline, HH option and VH option) for an input wind of 45 m/s that subtends an angle of 45 degrees to the x-axis. Wind solutions are calculated for inner, mid and outer swath locations (at 300, 550 and 900 km across-track, respectively). The plots illustrate that wind retrieval errors at extreme wind are dominated by uncertainty in wind direction. We observe that the wind vector retrieval (i.e. wind speed and direction) is superior with the HH option but only over outer swath cells. The ambiguity rejection is better with this option too, but at the expense of a secondary wind solution that is strongly biased in wind speed, yielding WSRMS scores that are worse than baseline over the mid-outer swath. This is unfortunate, because it renders wind vector solutions vulnerable to biases depending on the accuracy of the a priori information. On the other hand, the addition of a VH capability results in a definitely improved determination of wind speed across the swath, this without procuring any directional information about the wind vector.

In summary, the VH option (VV with VH on mid beam) offers improved performance over the entire the swath with a wind speed RMS error under 0.5 m/s at extreme winds, while the HH option (HH with VV on mid beam) offers improvement over a more limited portion of the swath with a wind vector RMS error down to 6 m/s but conditioned to the

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![Fig. 11. Output wind probability arrays (input wind 45 m/s @ 45 deg is cross-haired): the introduction of HH beams in the fore/aft antennas affords an improved determination of the ocean surface wind vector RMS error just over outer swath cells, while the introduction of a VH capability in the mid beam affords improved](image-url)
availability of high quality a priori NWP information to operate the ambiguity resolution.

In principle, one could conciliate the two alternatives by forming a composite configuration that held HH beams in the fore/aft antennas and a VH+VH capability in the mid beam. Their strengths would merge into a system that operates nominally at low to moderate winds (4 to 25 m/s) and optimally in the extreme high wind speed range (25 to 65 m/s). The VH capability in the mid beam would provide an improved determination of the wind speed across the swath, while the HH capability in the fore/aft beams would afford an improved determination of wind speed and direction for outer swath cells. The VV capability in the mid beam would limit deterioration due to the utilization of weaker HH signals at low winds, likely guaranteeing that the system behaves close to nominal in the low to high wind speed range (4 to 25 m/s). However optimal, cost and complexity constraints should put a single VH capability in the mid-beam antenna before a composite configuration.

IV. SUMMARY AND CONCLUSIONS

The wind retrieval performance in the range of 0-25 m/s of a fixed fan-beam scatterometer operating at C-band in VV polarization (ASCAT-type) is well established. Extreme wind speeds above 25 m/s are of particular interest as these occur over sea in both tropical and extra-tropical hurricanes (>34 m/s) with often devastating consequences. In both types of hurricanes, severity is indicated by a wind speed scale and wind speed knowledge is essential, while wind direction tends to be rather systematic and predictable (circular and uniform). With the aim of improving the wind retrieval performance of an ASCAT-type scatterometer at extreme wind speeds (25 to 65 m/s), prospective extension to VV polarization with HH and VH polarized beams are presented in this manuscript. The Geophysical Model Functions (GMFs) for C-band VV, HH and VH polarized backscatter used in the wind retrieval simulations are defined, along with an objective assessment of the quality scores ascribed to the different beam configurations. There is a limited number of polarization options that improve the scatterometer wind retrieval under extreme wind conditions (25 to 65 m/s) without detriment to the nominal instrument operation at low to high winds (4 to 25 m/s). The options include the introduction of a VH capability in the mid-beam antenna of an ASCAT-type scatterometer, and the introduction of HH beams in the fore/aft antennas. The VH option provides improved sensitivity to wind magnitude at extreme winds over the entire swath, with wind speed RMS errors of about 0.5 m/s (versus 1-5 m/s for the reference VV configuration in the same regime). The HH option provides good sensitivity to wind speed and direction over a more limited section of the outer swath, with wind vector RMS errors as low as 6 m/s (versus 7-10 m/s for the reference VV configuration) but conditioned to the availability of a priori information to resolve the wind vector ambiguity, which may give way to large wind speed biases when done inaccurately. Wind retrieval errors at extreme winds are dominated by uncertainty in the retrieval of wind direction. If the determination of wind speed primers over the determination of wind vectors at high wind speeds, then the introduction of a single VH capability in the mid-beam antenna comes forth as the most simple and cost-effective solution.

REFERENCES


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