CFOSAT 2nd International Science Team Meeting
15-18 March 2021

# Ku-band Polarization Difference Model From SCAT Measurements

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# Outline

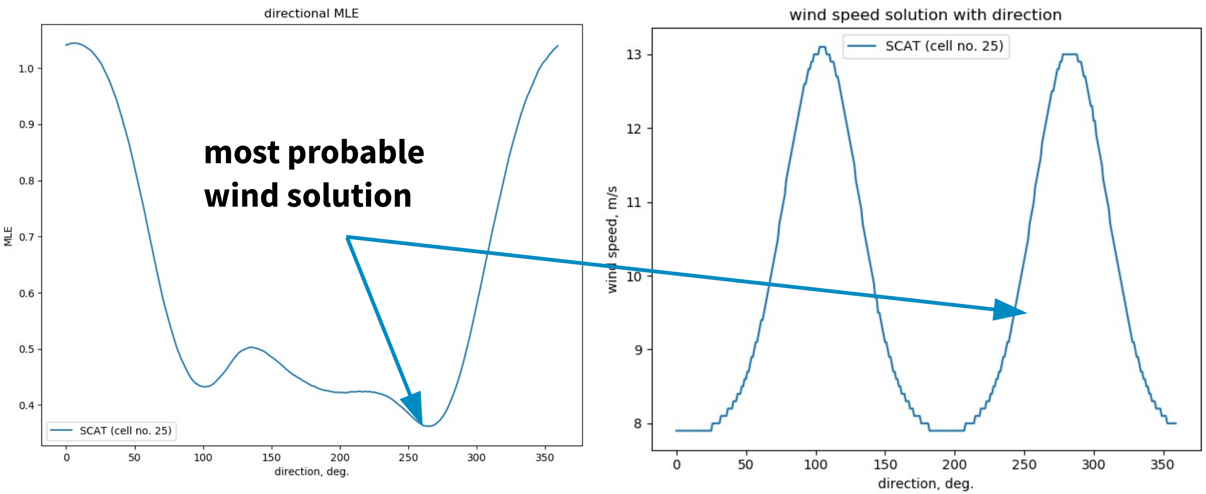
- Introduction to scatterometer inversion proiciples, the role of Geophysical Modulation Function (GMF)
- Existing Ku-band GMFs, common processing approach
- Sea surface statistical properties and radar signal  polarization: theoretical description
- Empirical GMFs and Polarization Difference (PD) theoretical GMF
- SCAT derived and theoretical Ku-band PD GMF properties
- Conclusions

# Scatterometer wind inversion approach

The standart scatterometer wind vector inversion procedure is based on the standard Maximum Likelihood Estimation (MLE) technique, where MLE cost function is axpressed as

$$J = \frac{1}{N} \sum_{i}^{N} \left( \frac{\sigma^0_{obsi} - \sigma^0_{modi}}{kp_i} \right)^2$$

The observed Normalised Radar Cross-section $\sigma^0_{obs}$ is compared with model $\sigma^0_{mod}$obtained from so-called Geophysical Modulation Fuction for the same azimuth and incidence angle.




***The example of directional MLE cost function estimated for single SCAT wind vector cell (left), and corresponding estimated wind speed directional variation (right).***

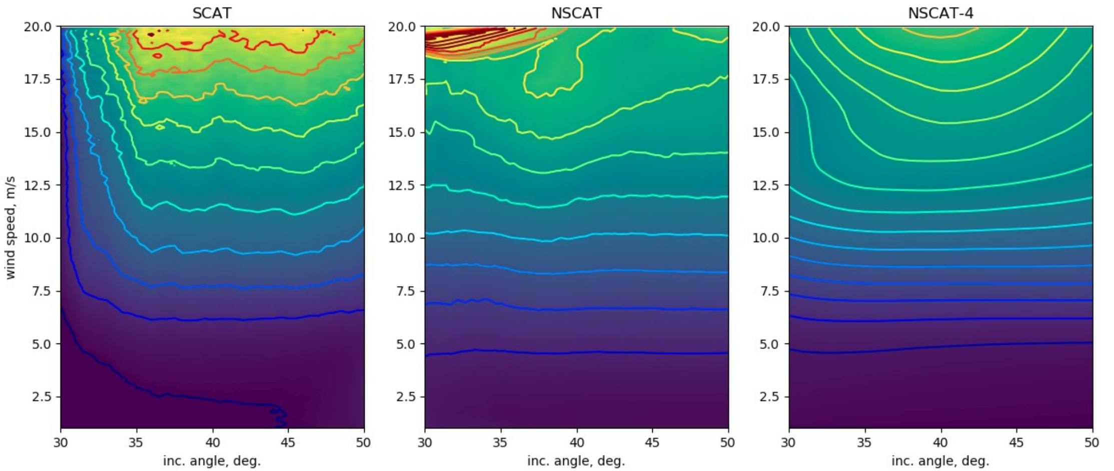
# Ku-Band Geophysical Modulation Function (GMF)

**Geophysical Modulation Function** is derived to describe relationships between Normalized Radar Backscattering Cross-Section (NRSC) mean and spectral properties with ocean sea surface statistical and forcing properties and plays a key role in scatterometry wind vector inversion algorithm.

Commonly, for each new instrument, a GMF is derived from massive collocations of radar measurements with global wind model outputs and offshore buoy network data. Very efficient, this empirical approach can still suffer to cover all environmental conditions, e.g. non-stationary sea state, sea surface current, sea surface temperature, etc.

For Ku-band instrument, a reference GMF is the NSCAT-4 GMF [e.g. Wentz, Smith 1999] which directly relates NRSC with wind speed and direction.

Our motivation is to propose a theoretical framework to help refine the analysis of sea surface backscatter properties and to extend the wind vector inversion algorithm.




*Examples of Ku-band empirical GMFs for (VV-HH)-pol, upwind dir . From left to right: SCAT one month observations, NSCAT (Quilfen et all. 1999), NSCAT-4 (Wentz, Smith 1999, KNMI)*

# The relation of radar measurements with sea surface wave statistical properties, governing equations

The NRSC is represented as a sum of polarized (BR) and non-polarized (NP) components

$$\sigma^{pol} = \sigma^{pol}_{br} + \sigma^{pol}_{np}$$

$^{pol}$ indicates vertical (V) or horizontal (H) polarization.

Assuming Gaussian distribution of tilting waves, to the second order in slopes, polarized component is expressed

$$\sigma^{pol}_{br} = \pi G^2_{pol} B(k_{br,\varphi})(1 + g_{pol} s_i^2 + h_{pol} s_i^2),$$

$$g_v = \frac{1}{2G_v^2}\frac{\partial^2 G_v^2}{\partial\theta^2},$$

$$g_h = \frac{1}{2G_h^2}\frac{\partial^2 G_h^2}{\partial\theta^2} + \frac{2}{\sin^2}\frac{|G_v|}{|G_h|}\frac{s_c^2}{s_i^2},$$

$$h_{pol} = M_t^{pol} M_h,$$

$$M_t = \frac{1}{G^2_{pol}}\frac{\partial G^2_{pol}}{\partial\theta},$$

$G_{pol}$ – geometric polarization coefficients

*B(k$_{br}$, phi)* - folded saturation spectrum at the Bragg resonant wavenumber

φ - azimuth from wind direction

θ – radar incidence angle

*$M_t$* and *$M_h$* the tilt and slope correlated parts of hydrodynamics modulation transfer function

For more details see Kudryavtsev et al. 2003 and Kudryavtsev et all. 2017

# Polarization Difference (PD) and semi-empirical wave model approach

The unknown non-polarized coefficient $\sigma_{np}$ cancels out by considering polarization difference (PD) .

$$\Delta\sigma = \sigma_v - \sigma_h$$

So, the expression for the PD model is following:

$$\Delta\sigma = \pi B(k_{br},\varphi)(\Delta[G^2_{pol}(1+g_{pol}s_i^2)] + \Delta[G^2_{pol}h_{pol}]s_i^2]\cos\varphi),$$

where $\Delta[x^{pol}]=x^v - x^h$ *is the polarization difference operator.*

The main unknown term in the above formulation is the saturation spectrum at Bragg wavenumber $B(k_{br}, \varphi)$. For wind speed range $3 < U_{10} < 20$ m/s, a first guess can follow the semi-empirical short wave spectrum model formulated in Yurovskaya et al. 2013, Kudryavtsev et al. 2014.

In contex of wind inversion the key parameters are following:

- The wind exponent $n$, in $B \sim U^n_{10}$
- The angular spreading of saturation spectrum $\delta$, related to omni-directional saturation spectrum $B_0(k_{br})$ as

$$B(k_{br},\varphi) = B_0(k_{br})(1+\delta\cos 2\varphi))/2\pi \qquad B_0(k_{br}) \doteq \int_0^{2\pi} B(k_{br},\varphi)d\varphi$$

# Data set

Historically, there are two Ku-band dual-polarized scatterometer radar providing space-born observations for wide range of incidence angles: NSCAT and SCAT. Theese data is suitable for the present PD analysis.

| Parameter name | *SCAT* | *NSCAT* |
|---|---|---|
| Frequency | 13.256 GHz | 13.995 GHz |
| Pointing inc. angle | 40° | 45° |
| Inc. angle range | 26° to 52° | 18° to 54° |
| Central $k_{br}$ | 357 rad/m | 415 rad/m |
| $k_{br}$ range | 244 to 438 rad/m | 181 to 474 rad/m |
| Mission dates | 24-11-2018 till now | 17-08-1996 to 30-06-1997 |
| Antenna type | dual-pol. rotating | six dual-pol. fixed |
| Swath width | ≈1100 km | two swaths, 600 km each |

***SCAT and NSCAT missions main instrumental parameters***

**Data involved for the analysis:**

- SCAT 40 days observations (September-October 2020): collocated CFOSAT Wind Data Processor (CWDP) processor output and ECMWF wind vector fields
- NSCAT analysis by Quilfen et al. 1999: collocated NSCAT, buoy and wind model data
- NSCAT-4 model, originally presented by [Wentz, Smith 1999], revised by KNMI: s the reference model for most Ku-band scatterometer data processors

# PD GMF, compare with existing empirical data

The expansion of PD model into a truncated Fourier serie gives:

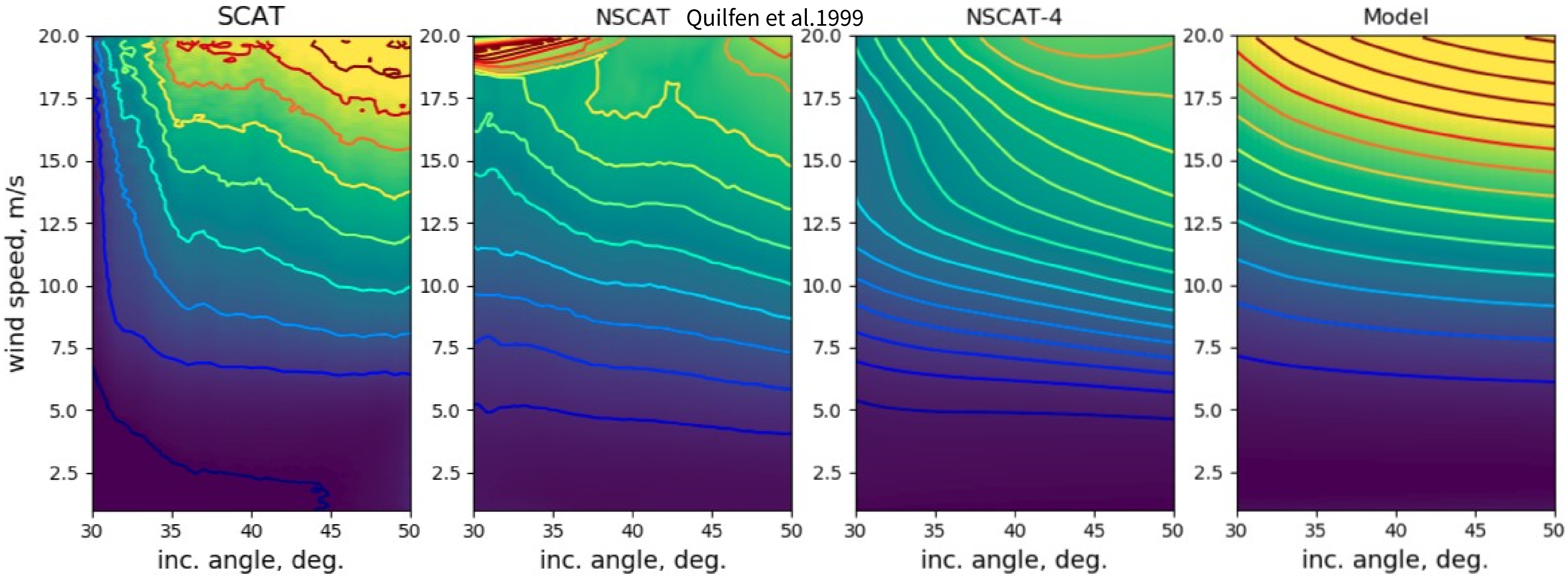
$$A_0 = B_0(k_{br})\Delta[G^2_{pol}(1 + g_{pol}s^2_i)]/2,$$
$$A_1 = B_0(k_{br})\Delta[G^2_{pol}h_{pol}s^2_i]/2,$$
$$A_2 = B_0(k_{br})\Delta[G^2_{pol}(1 + g_{pol}s^2_i)]\delta(k_{br})/2.$$

The same Fourier coefficients can be obtained directly from radar measurements:

$$A_0 = (\Delta\sigma^{up} + 2\Delta\sigma^{cross} + \Delta\sigma^{down})/4$$
$$A_1 = (\Delta\sigma^{up} - \Delta\sigma^{down})/2,$$
$$A_2 = (\Delta\sigma^{up} - 2\Delta\sigma^{cross} + \Delta\sigma^{down})/4$$

The empirical omni-directional saturation spectrum is

$$B_0(k_{br}) = \frac{2A_0}{\Delta[G^2_{pol}(1 + g_{pol}s^2_i)]}$$



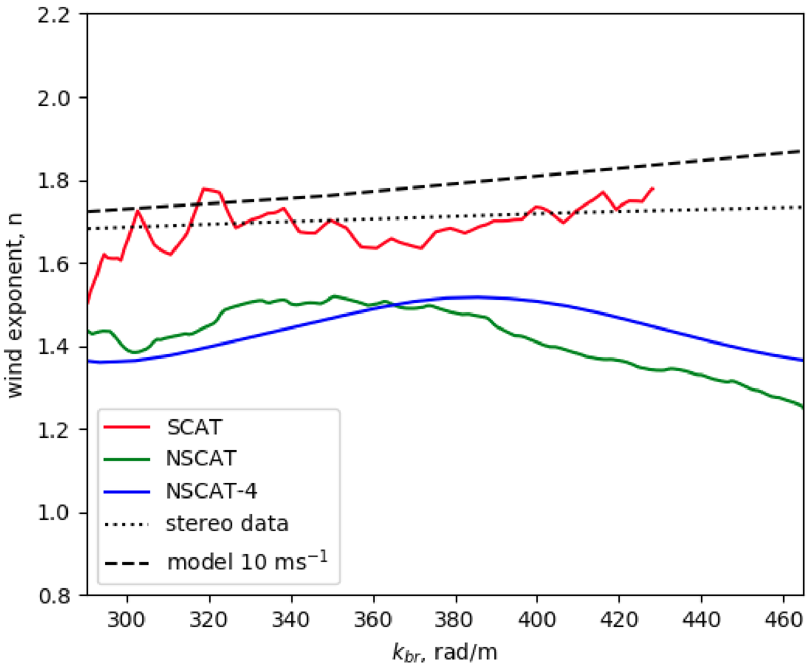

Empirical and theoretical models exhibit close results !

***Omni-directional curvature spectrum B0 estimated from polarization difference obtained with different empirical GMFs and theoretical model.***

# Ku-band PD GMF properties against SCAT and NSCAT measurements (wind sensibility)

The wind exponent *n*, in $B \sim U^{n}_{10}$ *shows the sensibility of radar observation to wind speed variations.*

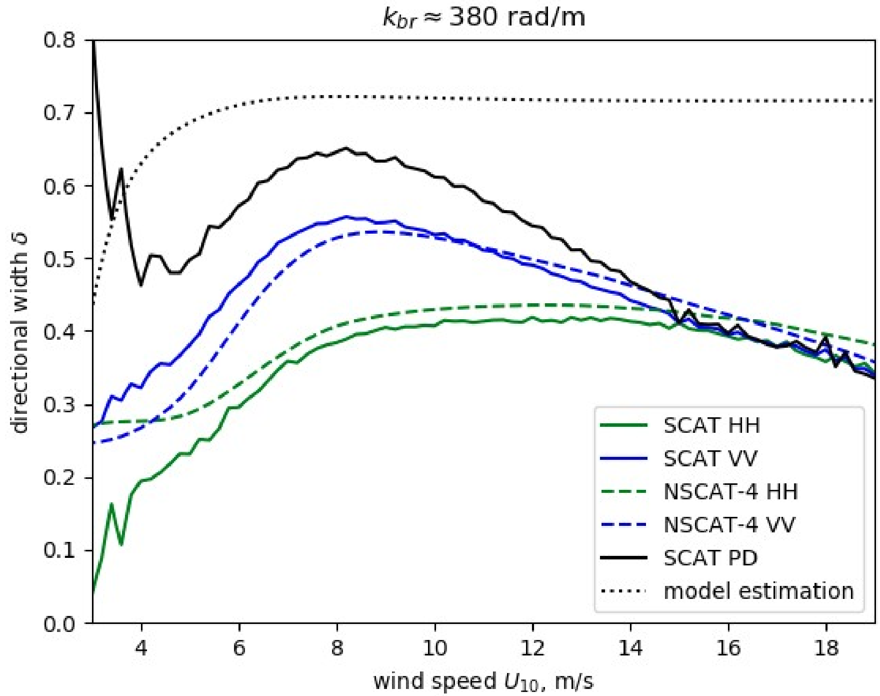
*The model, radar-derived and experimental measurements (stereo photography) show pretty similar values for Ku-band specific* $k_{br}$




***Wind exponent estimated from SCAT and NSCAT observations. Dotted line corresponds to field stereo photography measurements by Yurovskaya et al. 2013 and dashed line shows Kudryavtsev et al. 2014 model estimations at 10 m/s wind speed.***

# Ku-band PD GMF properties against SCAT and NSCAT measurements (directional width)

The angular width parameter δ  characterizes the wind direction sensitivity. The model and radar observations are consistent for low and moderate wind speeds. For high winds, radar-derived δ slightly decreases, while the predicted model angular width remains on the same level. This difference between the model and radar measurements may be explained by the limited growth of short capillary-gravity (1.5 cm) waves in the wind direction due to increased influence of the surface drift current on short wave dissipation, discussed in Quilfen et al. 1999



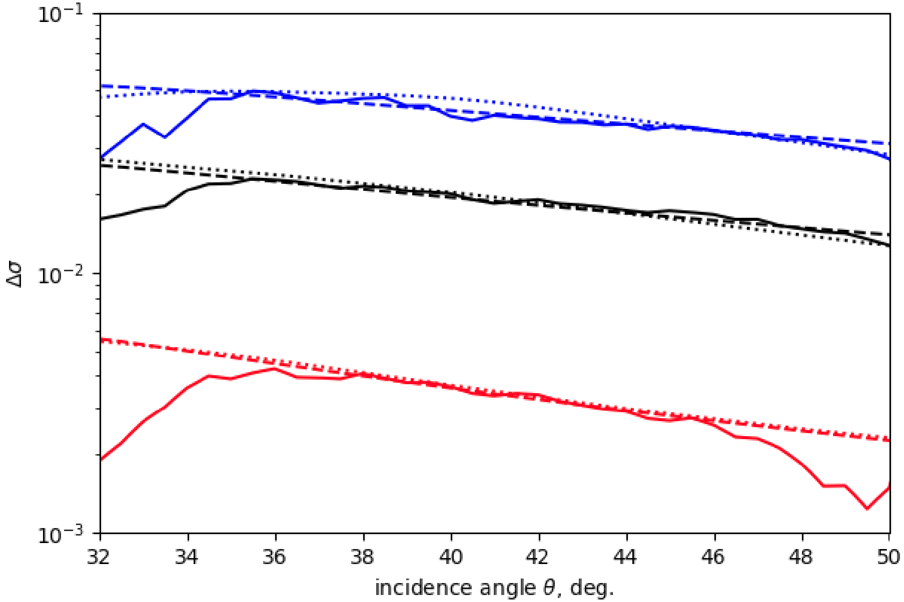

***Model directional width against SCAT and NSCAT observed values.***

# Ku-band PD model properties versus SCAT and NSCAT measurements

For wind inversion a PD GMF can be formulated the final form:

$$\Delta\sigma = \Theta(\theta) B_0(\theta)\left(1 + \delta(U_{10})\cos(2\varphi)\right) \times \left(\Delta[G_{pol}^2(1 + g_{pol} s_i^2)] + \Delta[G_{pol}^2 h_{pol}] s_i^2] \cos\varphi\right)$$

$\Theta(\theta)$ is a calibration factor (here parameterized in the form $\Theta = a\, tan(\theta)^m$, a~1, m~ ±1), aimed to correct antenna gain pattern residual and instrument calibration issues. An anisotropy factor $\delta(U_{10})$ is also considered to adjust with empirical GMFs for a more realistic behavior under high wind speeds.




***The polarization difference estimations for different Ku-band models for $U_{10}$ = 5 (red), 10 (black) and 15 (blue) m/s. Dot lines correspond to NSCAT-4, solid lines to SCAT and dashed lines show the present model***

# Summary and conclusions

- PD model closely reproduces the main properties of empirical radar GMFs in the range of $3 < U_{10} < 20$ m/s
- proposed analytical framework is a physically-driven approach to more precisely include any necessary additional local environmental effects, e.g. sea surface current and temperature effects, and/or presence of biological films
- The new inversion scheme could be proposed, where GMF adapted to every particular geophysical situation.
- The proposed model is ready to be implemented to complement the present SCAT processor.
- The present analysis is valid for other microwave sensing bands and, could be extended to radar Doppler measurements.