Analysis of the scatterometer ocean surface measurement dependency on sea state: an update

Federico Cossu [1], Ana Trindade [1,2], Marcos Portabella [1], Anton Verhoef [3], Ad Stoffelen [3]

[1] Institut de Ciencies del Mar (ICM-CSIC)

[2] University of Oldenburg

[3] Royal Netherlands Meteorological Institute (KNMI)

International Ocean Vector Winds Science Team Meeting

Darmstadt, Germany, 05-08 May 2025

BEC

Barcelona Expert Center

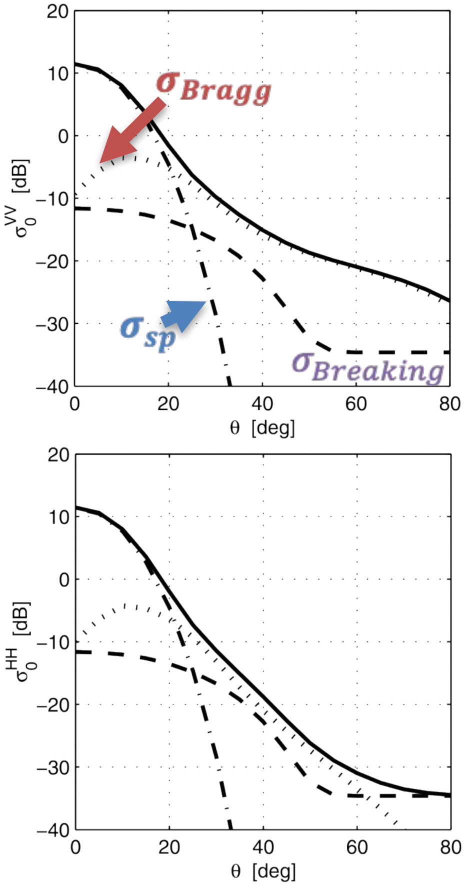
Motivation

- Recent Synthetic Aperture Radar (SAR) work confirms the different ocean surface scattering mechanisms for vertically (VV) and horizontally (HH) co-polarized measurements of the Normalized Radar Cross section (NRCS).
- VV modulation is well described by the so-called Bragg scattering of electromagnetic waves on wind-generated gravity-capillary ocean waves.
- It is of interest to also investigate the other ocean surface electromagnetic wave scattering mechanisms, associated with horizontally-polarized microwaves (wave breaking statistics).
- The HH NRCS depends both on the local wind and the non-locally generated waves that propagate through the scatterometer Wind Vector Cell (WVC).
- The aim of this study is to thoroughly analyze sea state conditions in association with HH (and VV) NRCS.

Conceptual model

$$\sigma_{0,PP} = \sigma_{Bragg,PP} + \sigma_{sp} + \sigma_{Breaking}$$

Non-polarized
σ_s



(slide courtesy of Paco López-Dekker)

Data

- Collocations between:
  - Ku-band dual-polarized scatterometer HSCAT-C (onboard the HY-2C satellite) 25 km product
  - ECMWF WAM sea state parameters
  - SST from ERA5

- Period analyzed: Dec 2021 – Mar 2022 (3 months, 1240 orbits)

- Scatterometer inversion residual is analyzed

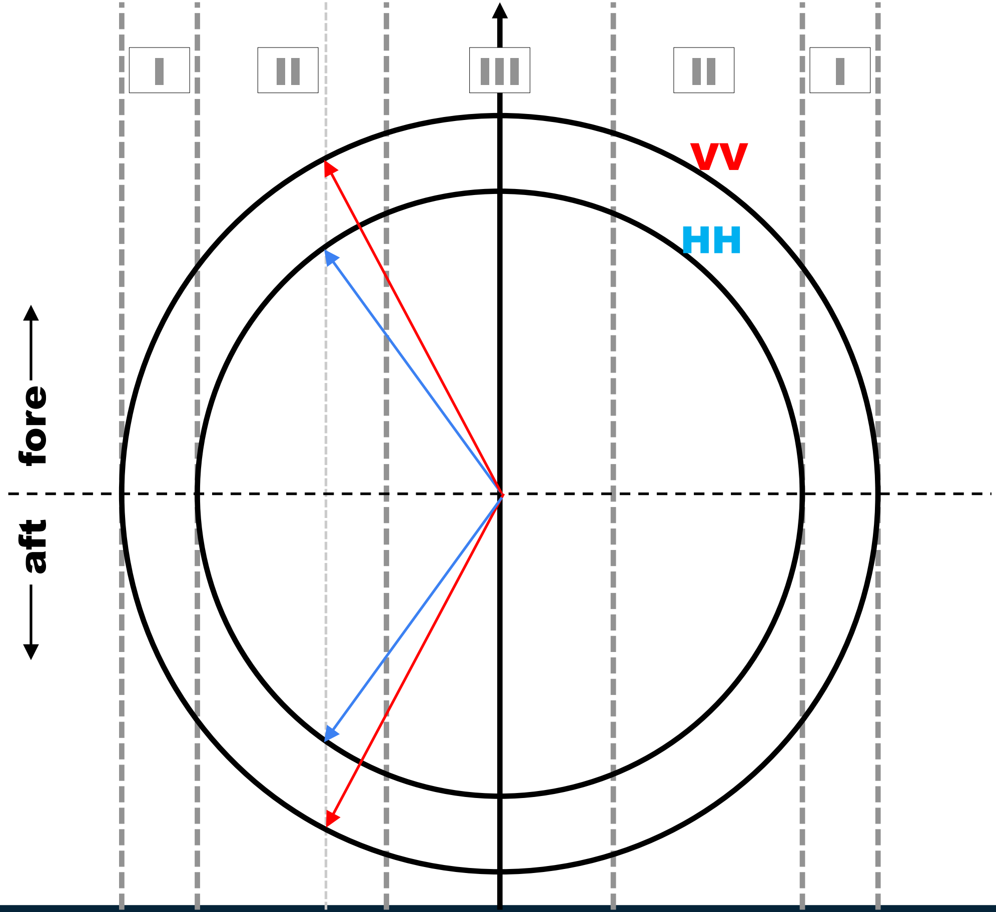
- Quality flags used for wind filtering: unfiltered (all points) and KNMI QC passed

Sea state parameters

The sea state parameters from the European Centre for Medium-range Weather Forecasts (ECMWF) wave model (WAM) are:

- **swh**: significant height of combined wind waves and swell.
  This parameter represents the average height of the highest third of surface ocean/sea waves generated by wind and swell. It represents the vertical distance between the wave crest and the wave trough.
- **shts**: significant height of total swell.
  This parameter represents the average height of the highest third of surface ocean/sea waves associated with swell.
- **pp1d**: peak wave period.
  This parameter represents the period of the most energetic ocean waves generated by local winds and associated with swell.
- **mpts**: mean period of total swell.
  This parameter represents the mean period of the waves associated with swell.
- **dwps**: wave spectral directional width for swell.
  This parameter indicates whether waves associated with swell are coming from similar directions or from a wide range of directions.
- **mwd / rwd**: mean wave direction / relative wave direction.
  This parameter is the mean direction of ocean/sea surface waves. It is a mean over all frequencies and directions of the two-dimensional wave spectrum. From this parameter, we compute the relative wave direction between the direction of the waves and the direction of the wind vector.

Rotating scatterometer geometry (HSCAT-C)



- Category I: outer regions (VV views only, poor azimuth diversity)
- Category II: sweet regions (HH+VV views, good azimuth diversity)
- Category III: nadir region (HH+VV views, poor azimuth diversity)

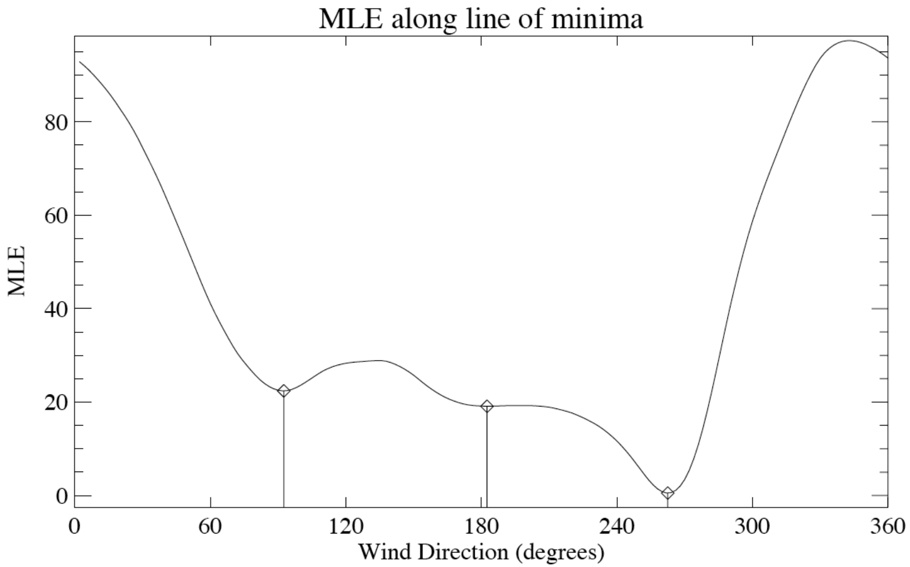
HH+VV views only available in the inner region (sweet + nadir region)

Relation between MLE and NRCS

- In scatterometry, the true wind solution is given by minimizing the cost function of the Maximum Likelihood Estimator (MLE), which depends on the NRCS (σ^0):

$$MLE = \sum_{i=1}^{4} \frac{\left(\sigma^0_{i,GMF} - \sigma^0_{i,meas}\right)^2}{Kp\left(\sigma^0_{i,meas}\right)}$$

- i=1,2,3,4 (the four possible views/measurements)
- $\sigma^0_{i,GMF}$: NRCS simulated through the Geophysical Model Function (GMF), it depends on wind speed and SST
- $\sigma^0_{i,meas}$: measured NRCS
- Kp: measurement error variance (noise)

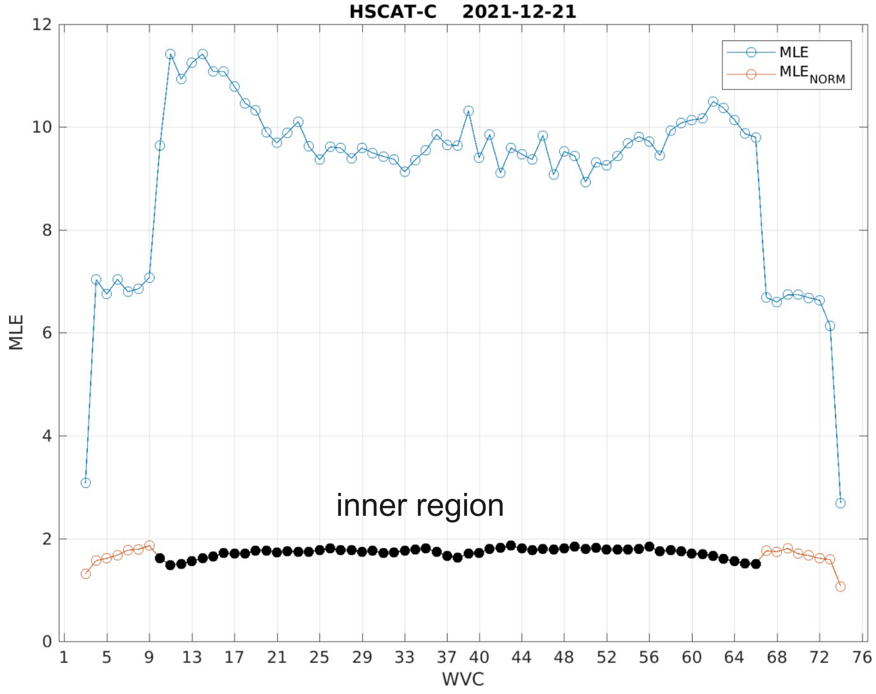


MLE is normalized by Kp, but it is not uniform across the swath (node number).

Normalized MLE

- To normalize MLE across the swath, MLE is divided by an expected MLE value ($\langle MLE \rangle$), which depends on the wind speed and node number.

$$MLE_{NORM} = \frac{MLE}{\langle MLE \rangle}$$



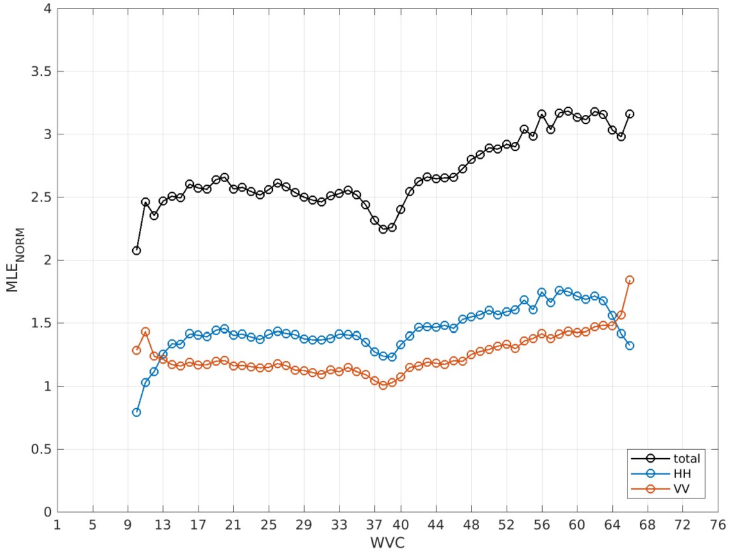
Only the WVC numbers from 10 to 66 (inner region with HH and VV views) are selected for the HH/VV decomposition.

MLE decomposition: HH and VV

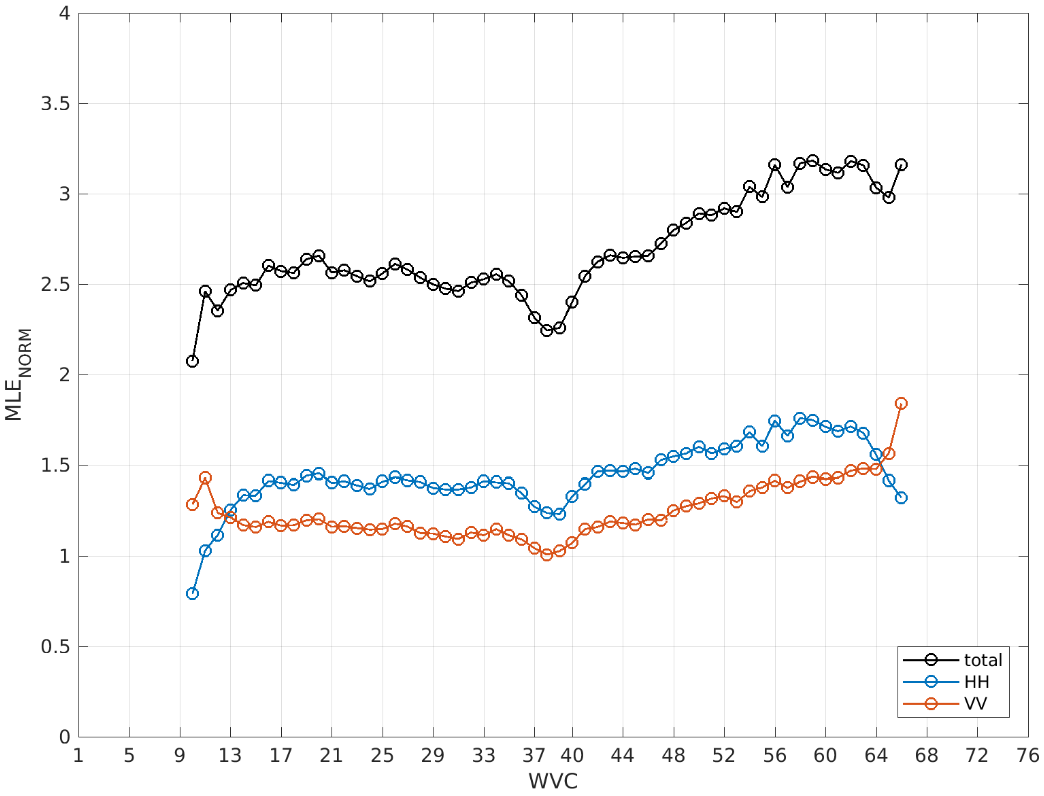
$$MLE = \sum_{i=1}^{4} \frac{\left(\sigma^0_{i,GMF} - \sigma^0_{i,meas}\right)^2}{Kp\left(\sigma^0_{i,meas}\right)} \longrightarrow MLE_{NORM} = \frac{MLE}{\langle MLE \rangle}$$

$$MLE_{HH} = \sum_{i=1,3} \frac{\left(\sigma^0_{i,GMF} - \sigma^0_{i,meas}\right)^2}{Kp\left(\sigma^0_{i,meas}\right)} \longrightarrow MLE_{NORM,HH} = \frac{MLE_{HH}}{\langle MLE \rangle}$$

$$MLE_{VV} = \sum_{i=2,4} \frac{\left(\sigma^0_{i,GMF} - \sigma^0_{i,meas}\right)^2}{Kp\left(\sigma^0_{i,meas}\right)} \longrightarrow MLE_{NORM,VV} = \frac{MLE_{VV}}{\langle MLE \rangle}$$

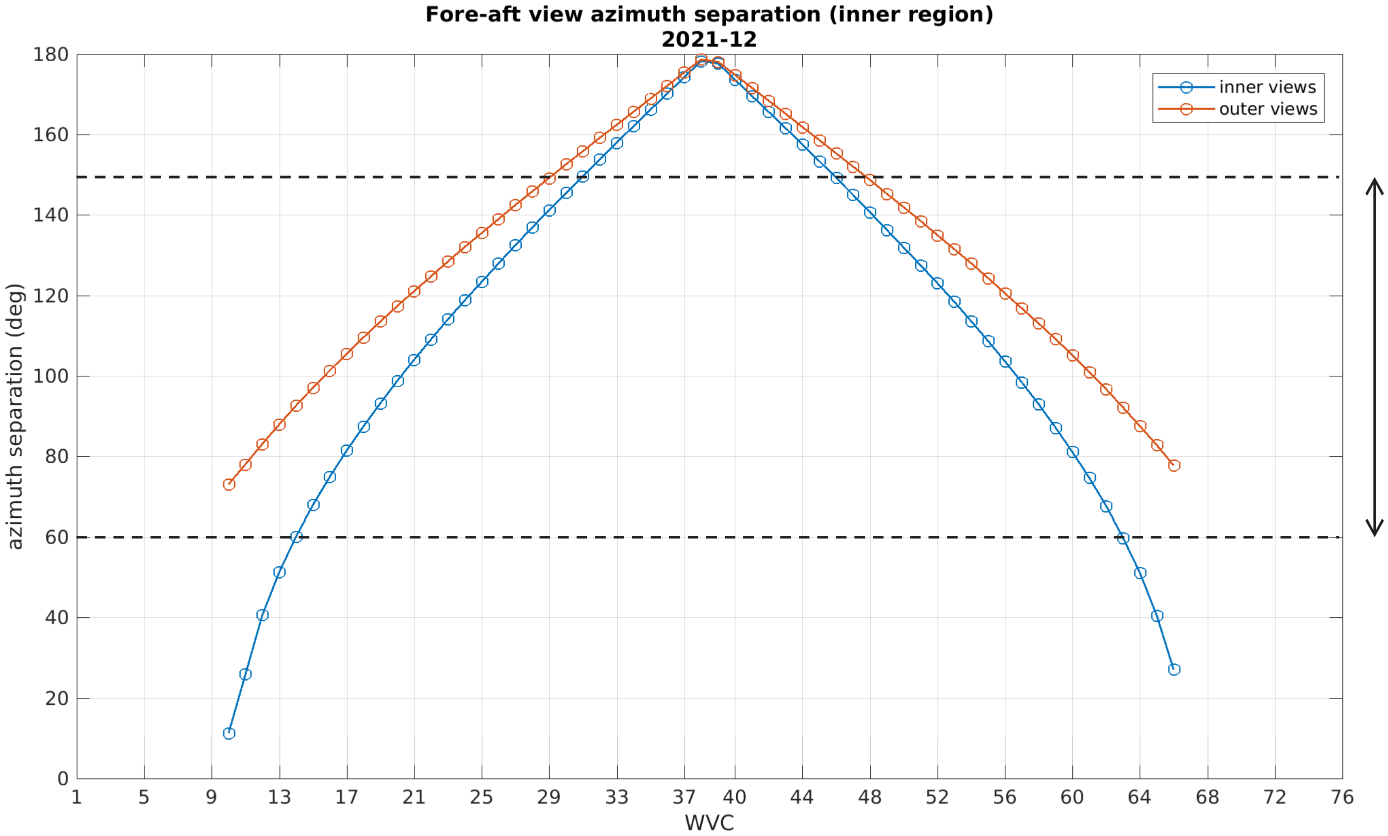


Normalized MLE (inner region)



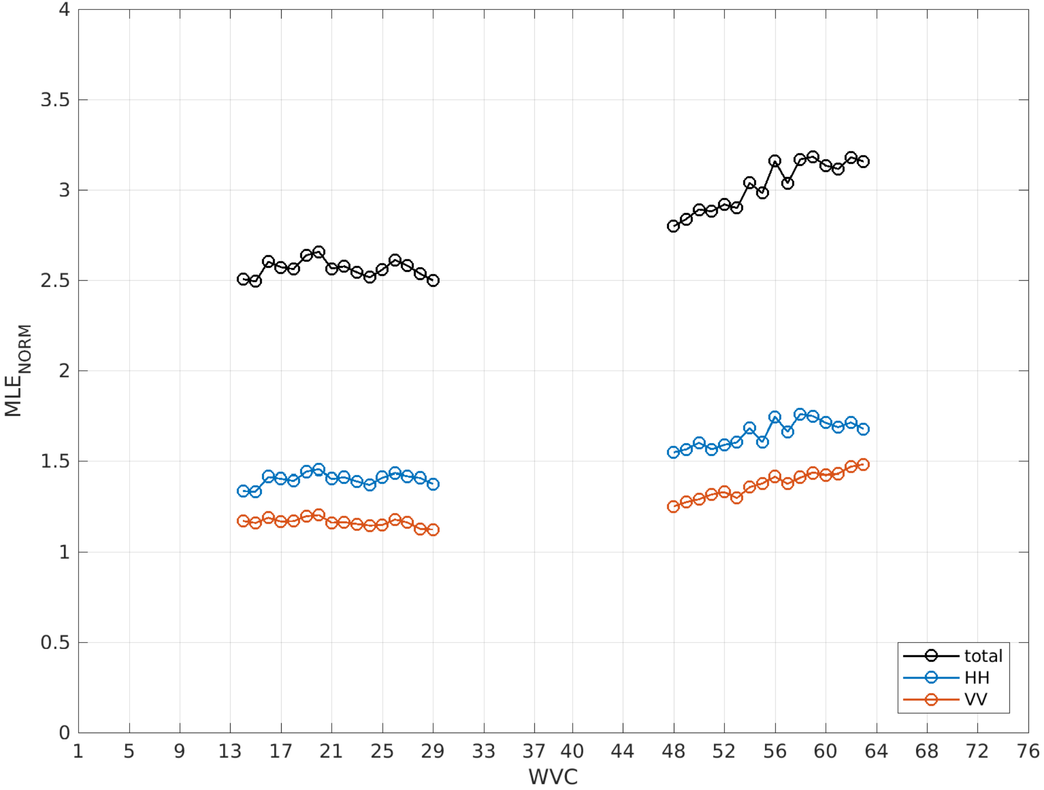
WVC: 10–66

Fore-aft views azimuth separation



optimal range

Normalized MLE (sweet region)



Azimuth separation:
60°–150°

WVC: 14–29 & 48–63

Sea state categories

Sea state categories identified with the method from Grieco et al., 2016.

$$H_S^{FD} = 0.22 \frac{U^2}{g}$$

$$\text{growing sea :} \quad H_S - H_S^{FD} \leqslant -0.44 \frac{U}{g} \Delta U$$

$$\text{fully developed sea :} \quad |H_S - H_S^{FD}| < 0.44 \frac{U}{g} \Delta U$$

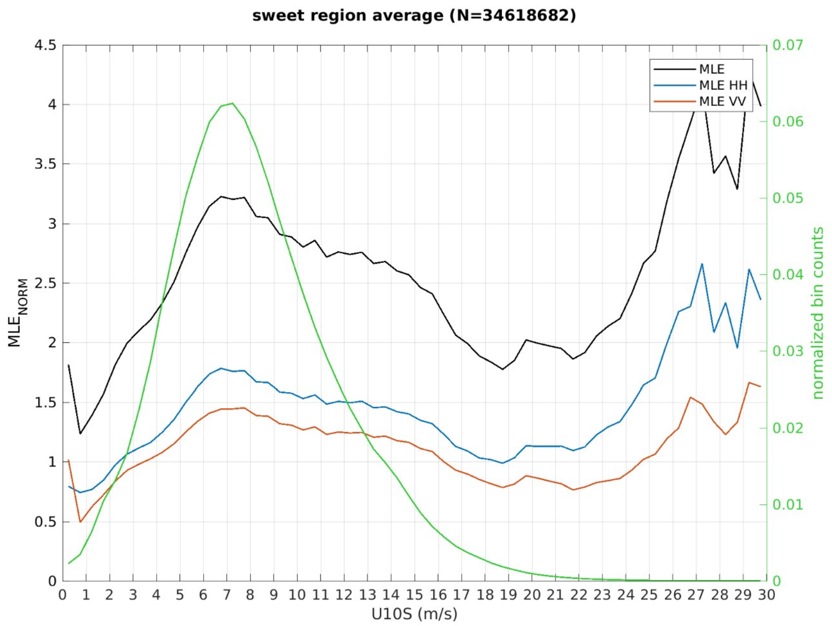
$$\text{decaying sea :} \quad H_S - H_S^{FD} \geqslant 0.44 \frac{U}{g} \Delta U$$

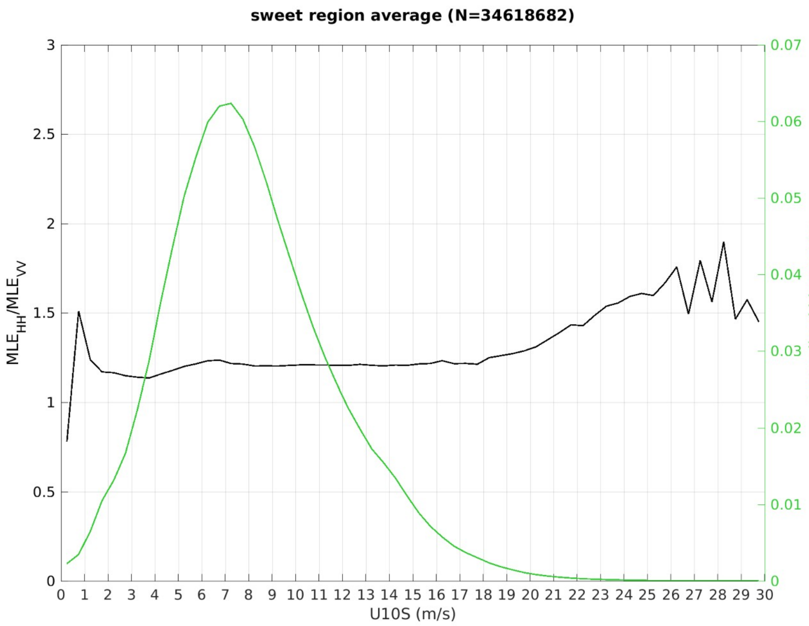
where:

- U: HSCAT-C wind speed (U10S)
- ΔU: 1.3 m/s
- g: gravitational acceleration

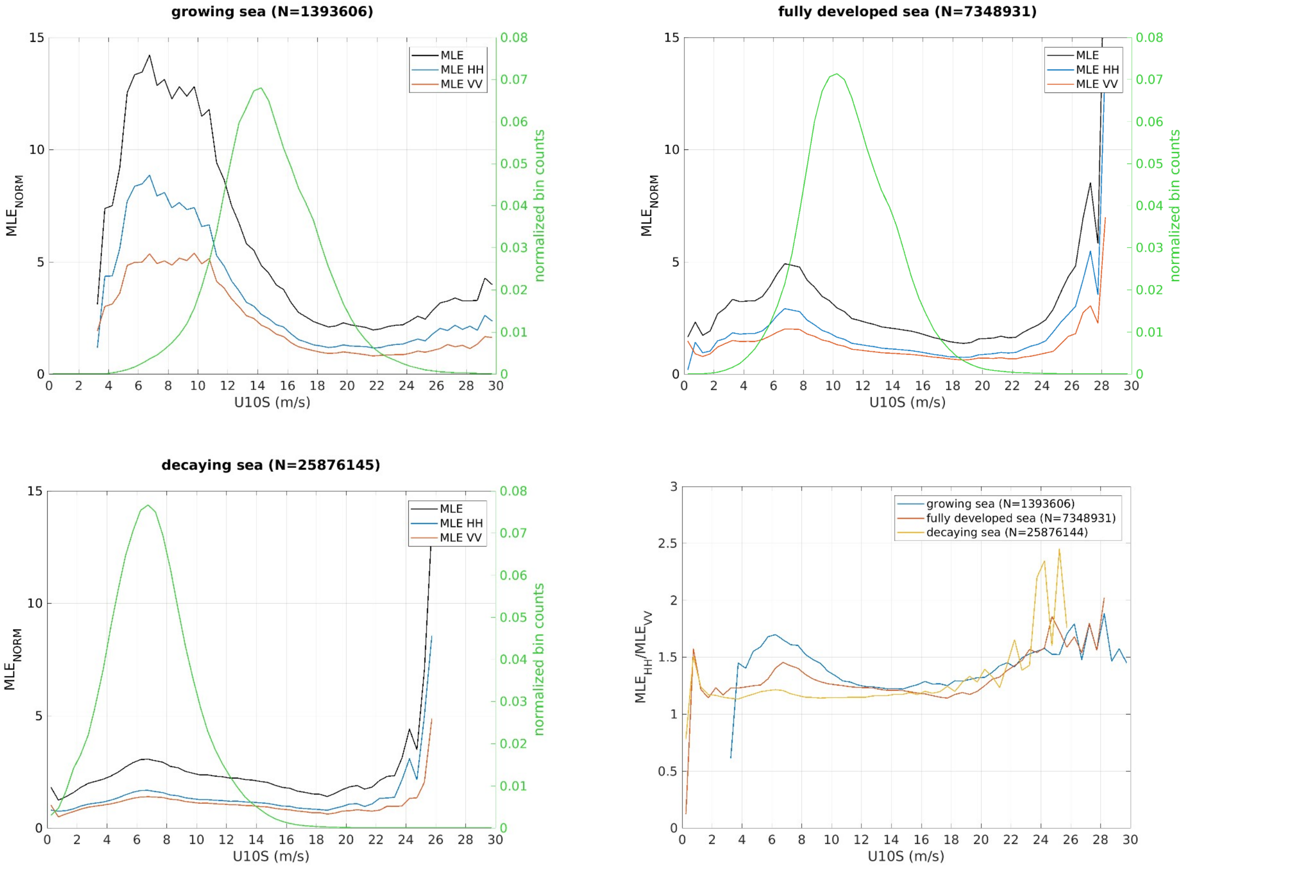
We found 4.1% samples for growing sea, 21.1% for fully developed sea and 74.8% for decaying sea.

Results: sweet region average (unfiltered winds)





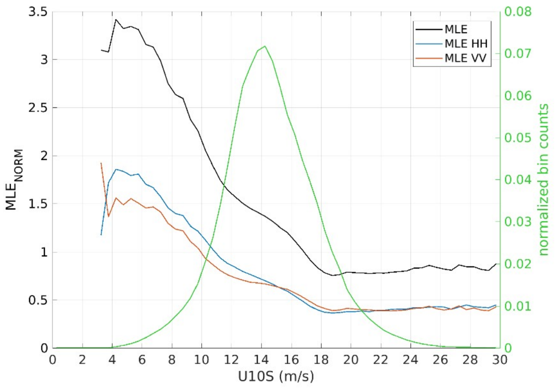
Results: sea state categories (unfiltered winds)



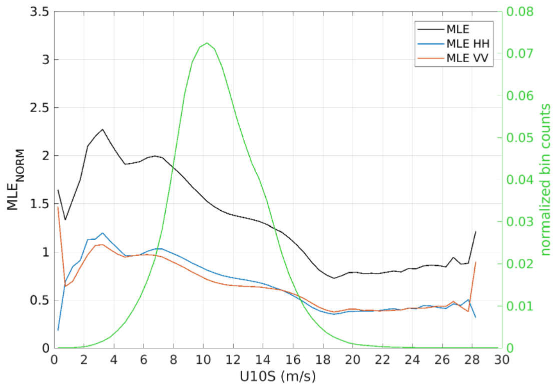
Results: sea state categories (KNMIQC-passed winds)

BEC Barcelona Expert Center

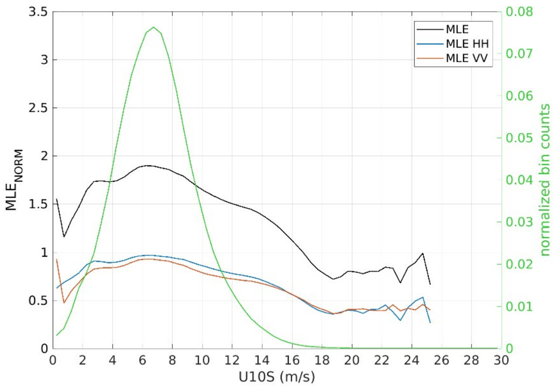
growing sea (N=1106758)

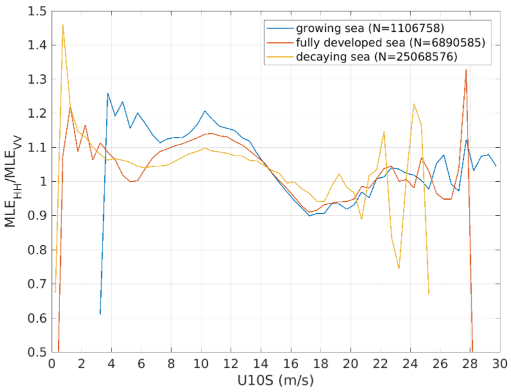


fully developed sea (N=6890585)

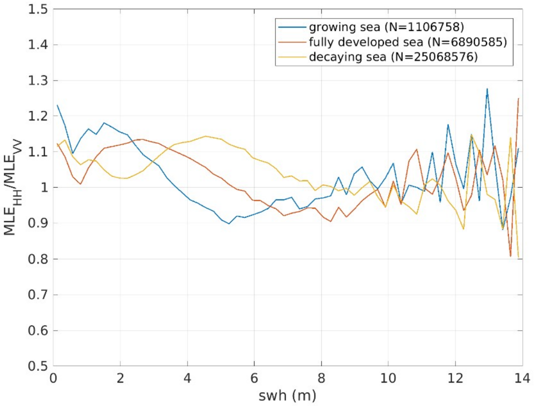


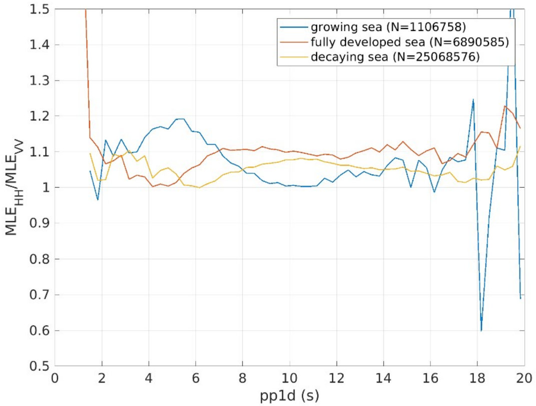
decaying sea (N=25068576)

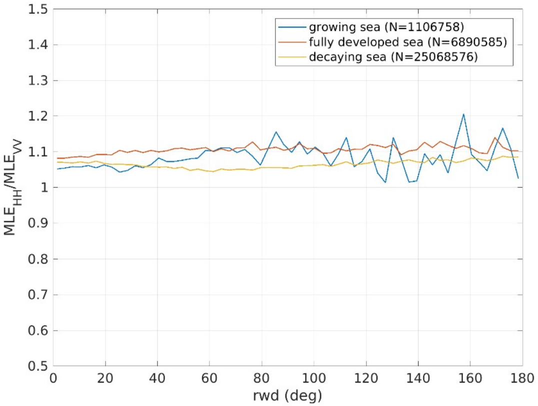


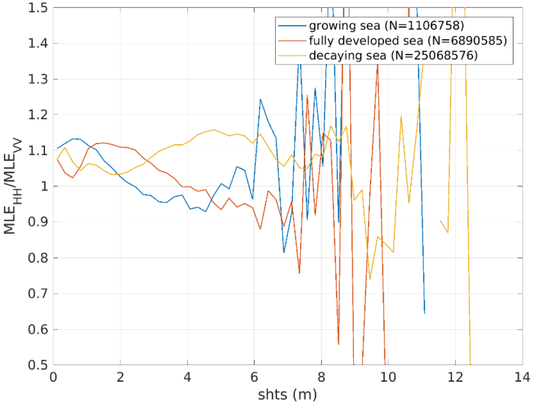


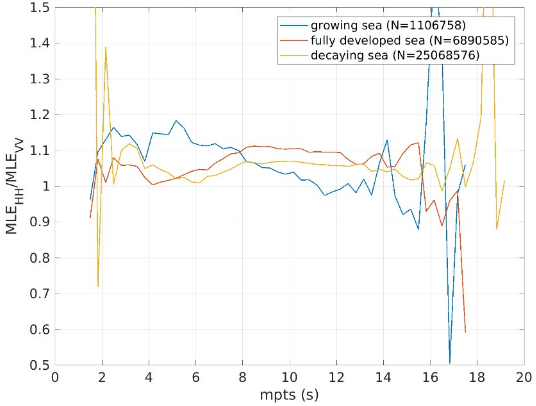
HH/VV ratio (KNMIQC-passed)

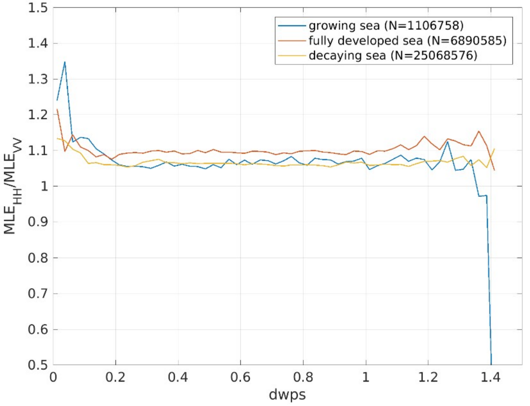












Conclusions and outlook

- Ku-band dual-polarization scatterometer measurements have the potential to highlight the non-polarized contribution due to the sea state, thanks to the different sensitivity of HH and VV NRCS to the Bragg scattering.
- MLE (wind inversion residual) is analyzed and compared to 6 sea state parameters + U10S
- The unfiltered winds show of a distinct HH (compared to VV) sensitivity to wind speed and sea state category, although such result is most probably due to rain effects.
- For the KNMI_QC-passed winds the HH/VV ratio is smaller compared to the unfiltered winds, proving the effectiveness of the QC on rain contamination removal.
- The sea state parameters related to wave height and wave period show a more complex behaviour of the HH/VV ratio (compared to U10S).
- The sea state parameters related to the directional properties show a rather uniform response across their range of values.

<u>Outlook:</u>

- Apply a new QC which removes rain more efficiently and keeps more good-quality high winds.
- Extend the analysis period.
- Extend the analysis to other Ku-band (ScatSat, HY-2 series) and C-band (ASCAT) scatterometers.

Acknowledgement: This work has been funded by the EUMETSAT OSI SAF through the OSI_VSA22_01 study.

Thank you!

BEC

Barcelona Expert Center