Validation and calibration of the 2km × 2km mitigation Doppler.

October 15th, 2025

SWOT Science Team meeting

Pierre Dubois (CLS),

on behalf of the CNES/JPL algorithm team

The SWOT Mitigation Doppler measurement.

In addition to SWOT's wide-swath altimetry capabilities, the mission concept provides some side products, among which

2-D Mitigation/ "High Resolution" Doppler image:

- The mitigation Doppler data product has been designed as an **additional product** with potential use in improving the SSH data product, by means of **sea state characterization**
- 2x2-km resolution and 2x2-km posting pixels centered at cross-track distances going from 10km to 56km on each side (=24 pixels per swath every 2km in along-track)

The pulse pair data content

Doppler is estimated using the pulse-pair method [Zrnic, 1977]. : $\mathrm{pp}(\tau) = v(t).\, v^*(t+\tau)$

The Pulse Pair Doppler captures any relative motion between the radar and the surface along the line-of-sight (in slow/azimuth time)

Measured Doppler = Non-Geophysical Doppler + Geophysical Doppler

<u>originates from</u>: The center of phase position in time + the ground projected antenna pattern shape.
It can be estimated using the POD, attitude reconstruction and antenna pattern best knowledge (STATIC_CAL data), by solving a geometric-based system of equations.

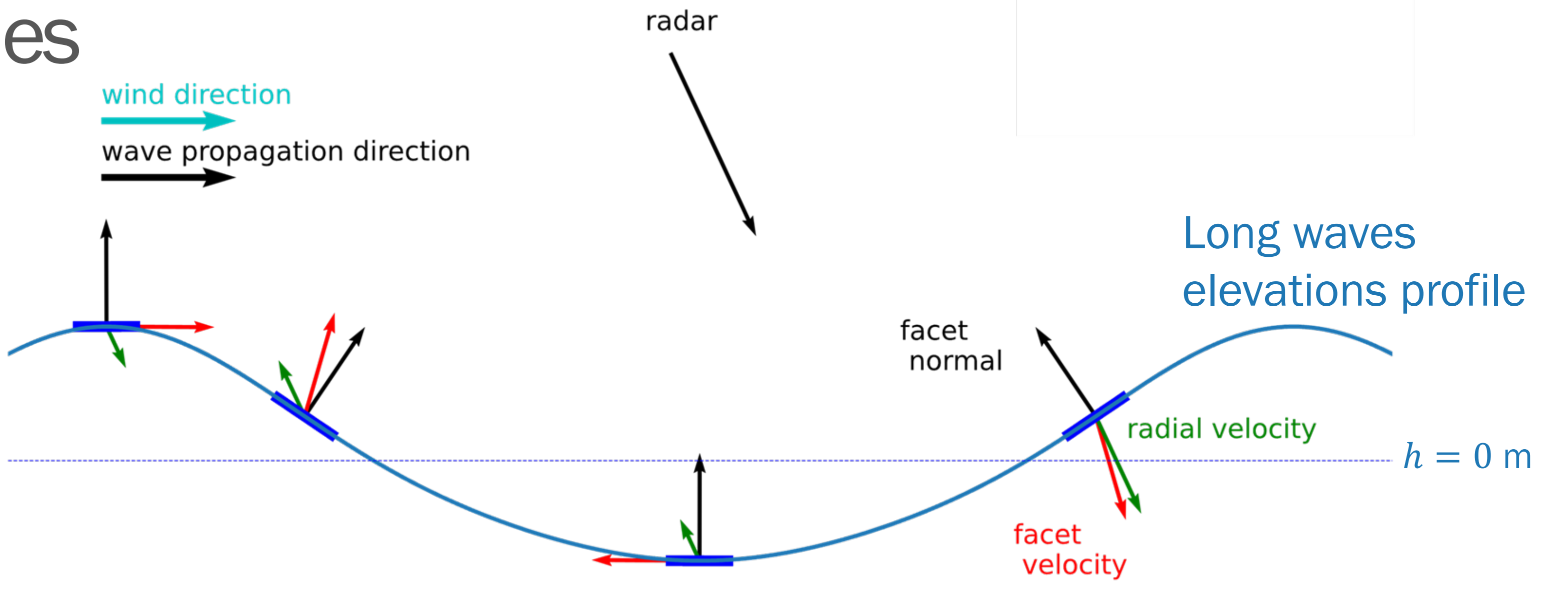
<u>originates from</u>: The surface motions:
surface currents
& waves orbital movement

Geophysical Doppler = (Measured Doppler – Non-Geophysical Doppler) can be estimated,

The effect of orbital velocities

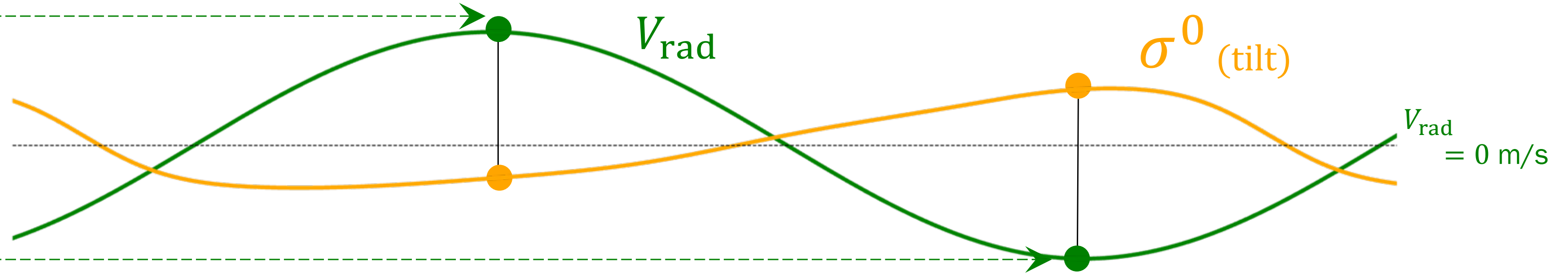
The pulse pair signal can be seen as the complex sum of a collection of facets supported by a long waves profile

$$\sum_{\text{facets}} \sigma^0 e^{-\frac{4\pi}{\lambda} i V_{\text{rad}} \tau}$$



In the collection,
If we pair up the facets of radial velocities of **same norms and opposite signs**, …

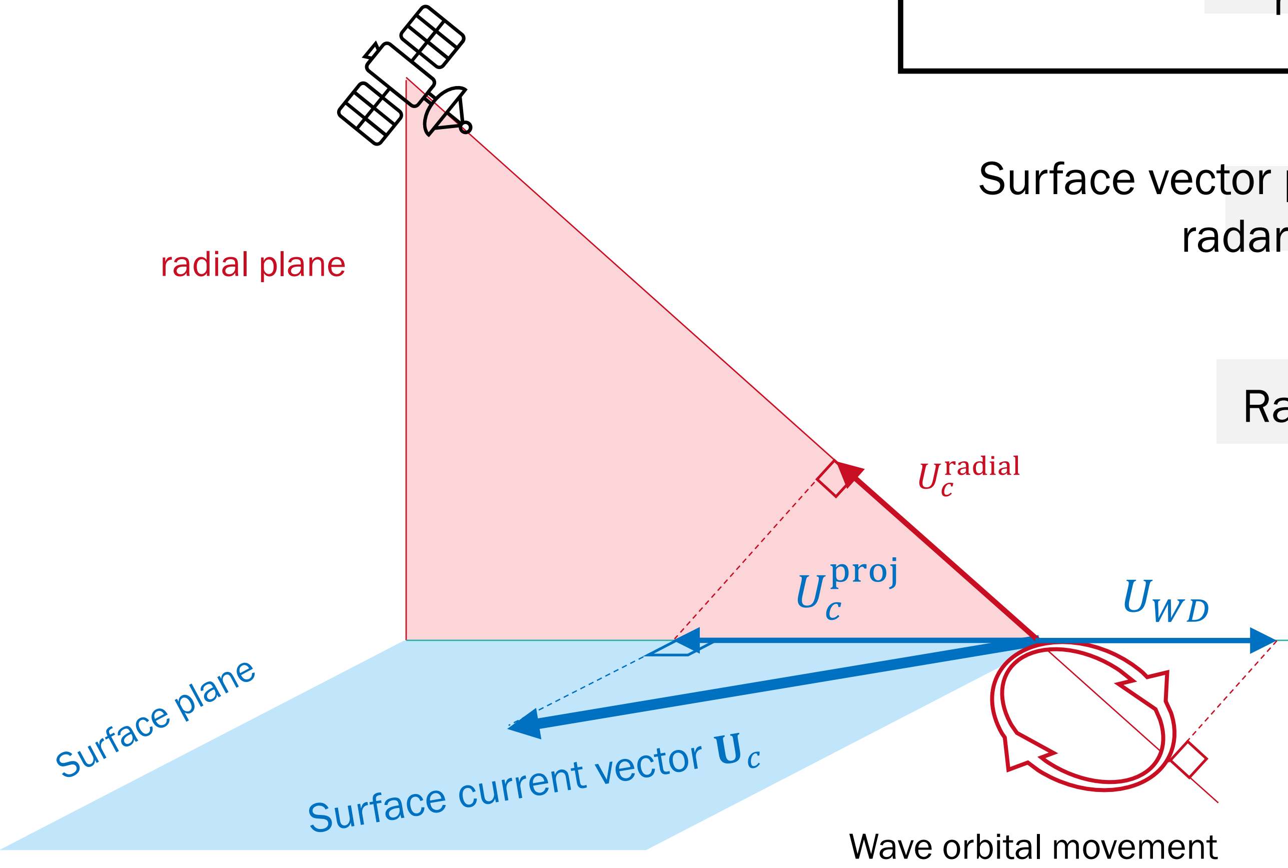
… they do NOT have the same σ^0
→ the facets phases of the pair do not compensate in the complex sum
→ a residual Doppler effect occurs



Model : $\text{Wave Doppler} = \alpha \, \mathbf{G} \cdot \mathbf{U}_{\text{Stokes}}$

([Chapron et al. 2005], [Nouguier et al. 2018])

Schematic contributions to geophysical velocity estimates



Surface vector	$\mathbf{U}_c$	
Surface vector projected in radial plane	U_c^{proj}	U_{WD}
Surface vector projected on radar line of sight	U_c^{radial}	U_{WD}^{radial}
Radar Doppler	$\text{Dopp}_c^{\text{radial}}$	Dopp_{WD}

Wave orbital movement

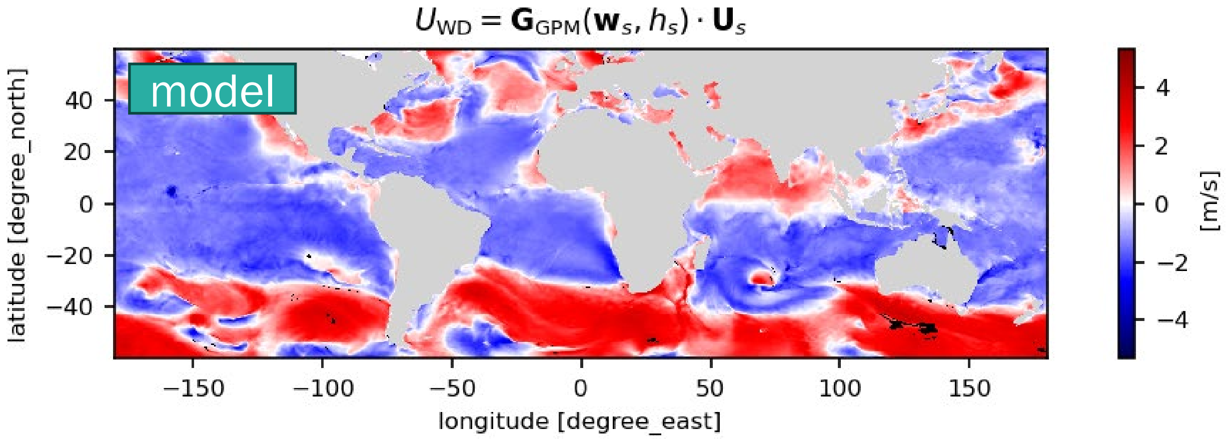
$$U_{GD} = U_{WD} + U_c^{\text{proj}}$$
$$U_{WD} = \mathbf{G} \cdot \mathbf{U}_{\text{Stokes}}$$

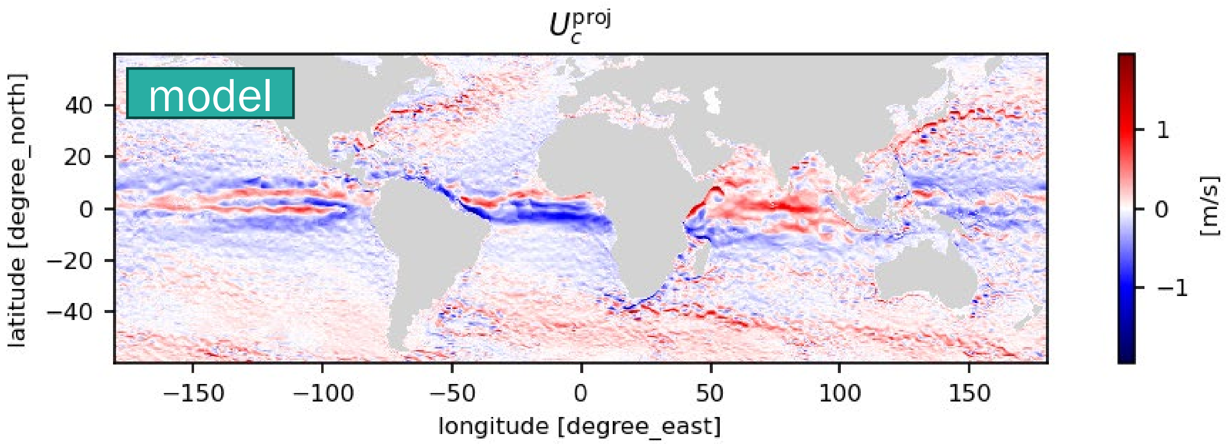
G is almost flat in incidence at near nadir, hence U_{WD} is, at constant sea state, constant within the swath

Projected currents and Wave induced currents: orders of magnitude

Incidence: 4° (far range)
date: 21 May 2025

$$U_{GD} = U_{WD} + U_c^{\text{proj}}$$





Here we illustrate the relative strength of each contribution (waves and currents) **purely** based on a sea state **model** (WW3) and on the SWOT (far range) geometry

The non-dimensional gain factor **G** has been derived with the use of Global Precipitation Measurement (JAXA/NASA) datasets,

<u>Inputs from models</u>
CCI_WW3 runs (credits M. Accensi, F. Ardhuin):

- Stokes drift vectors
- Surface current vectors
- Wind vectors
- Significant wave height

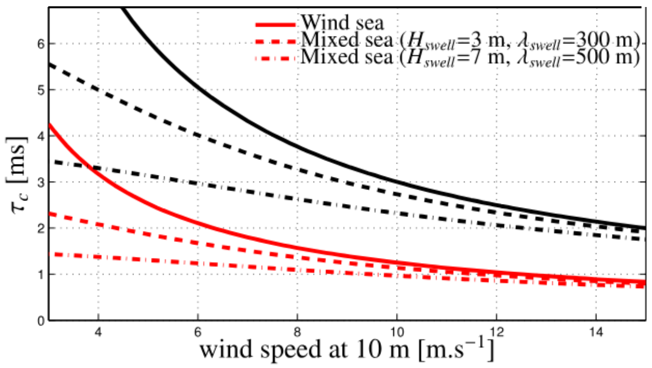
In black, locations where the couple (w_s, h_s) is outside the ranges of definition of $\mathbf{G}_{\text{GPM}}$

Horizontal velocities estimates performance

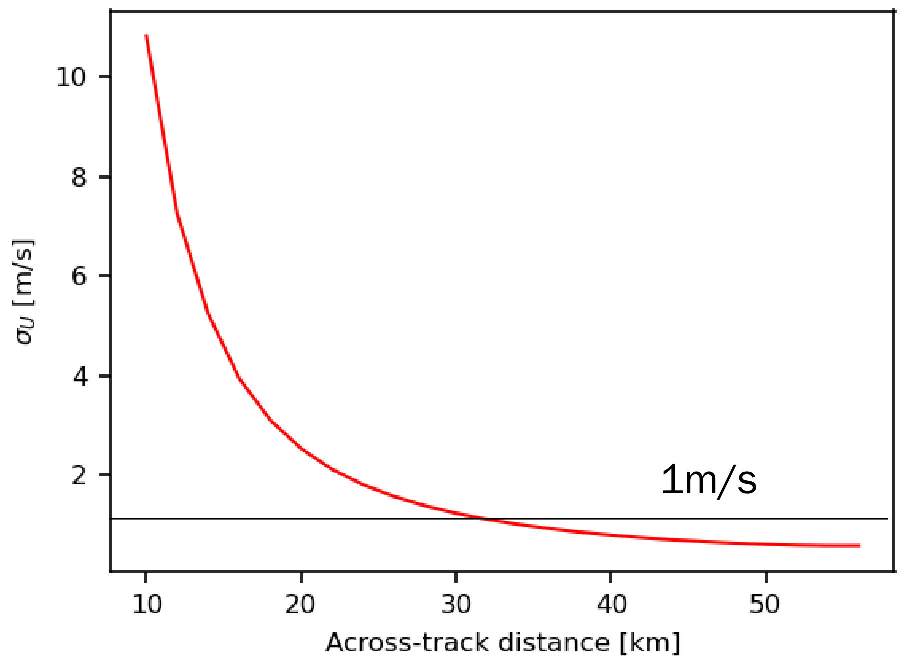
The Phase Perturbation Approach ([Zrnic, 1977]) is used to evaluate the pulse pair phase variance and then the projected velocities standard deviation.

The PPA uses a model for the pulse pair correlation, which must account for the following elements [Rodriguez et al 2018]

- the Signal to Noise Ratio decorrelation
- the Doppler decorrelation
    - originates from the variety of non-geophysical Dopplers along the azimuth direction of the resolution cell.
- the sea clutter/speckle temporal decorrelation (~1.5ms)



from [Boisot et al. 2016]: Correlation time τ_c in Ka-band (red lines) and Ku-band (black lines) at nadir as a function of wind speed at 10m.



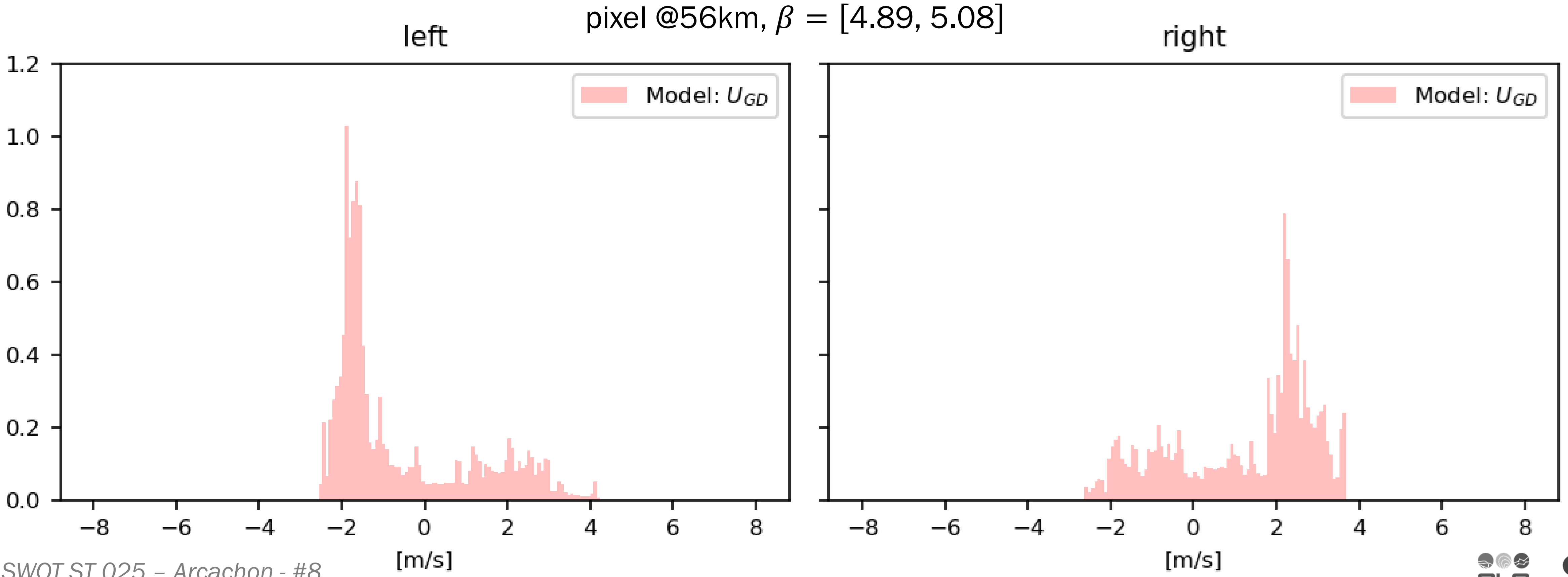
Standard deviation of the projected estimated velocities, function of the across-track distance

A statistical view of data validity

*the *beta angle* is the angle between a satellite's orbital plane around Earth and the geocentric position of the Sun.

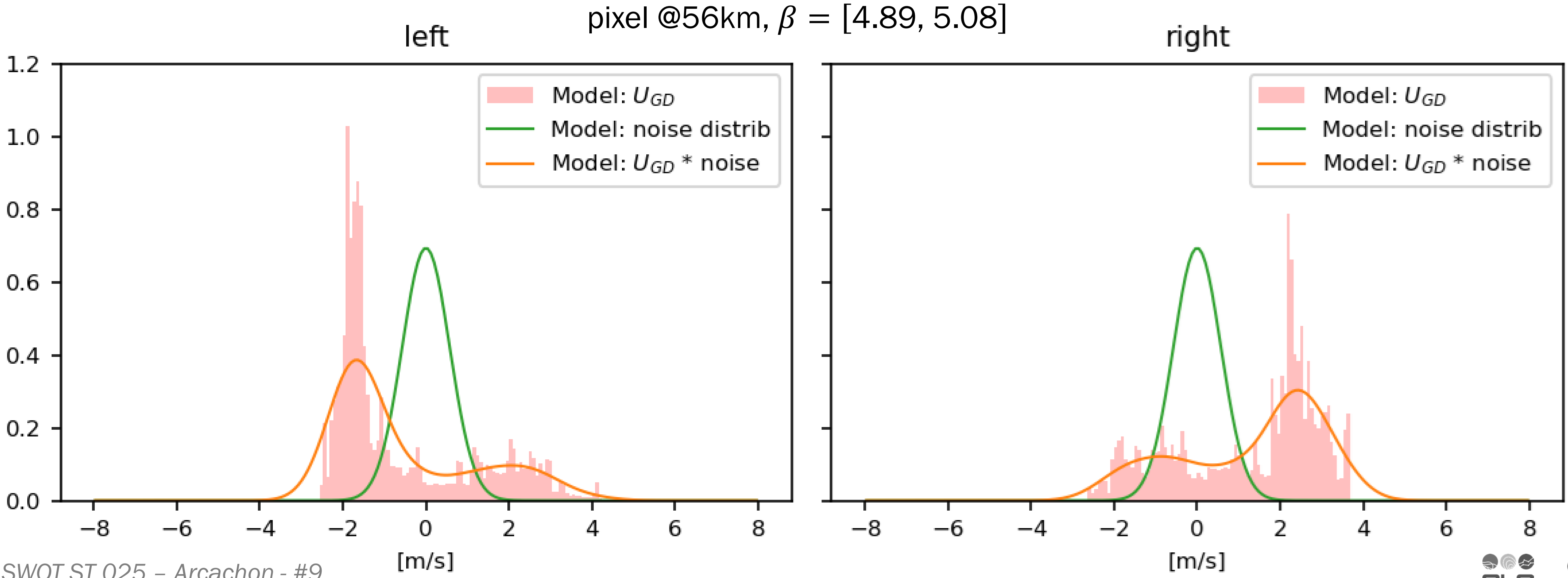
For a given across track pixel, and fixed beta angle*

The total geophysical current U_{GD} is modeled using the WW3 inputs, as described earlier



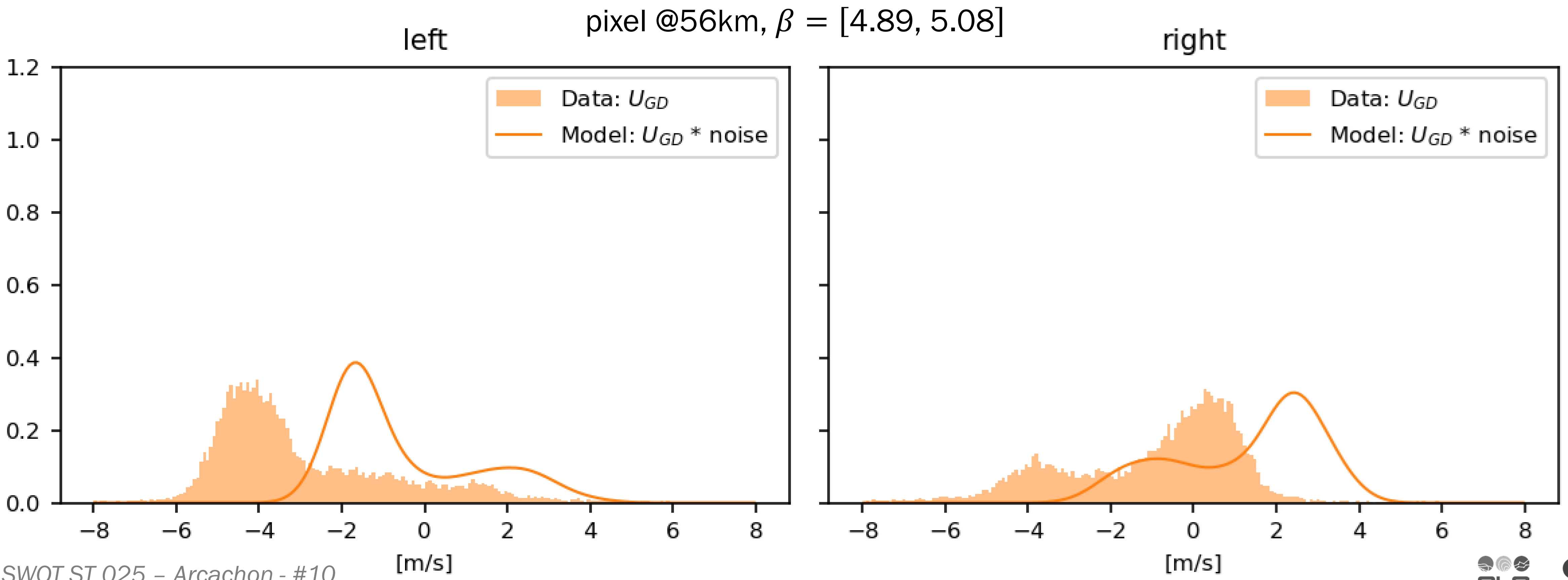
A statistical view of data validity

U_{GD} is convoluted with the noise distribution, a centered Gaussian of standard deviation set by our modeling.
→ it sets the **expected histogram of the observed U_{GD}**



A statistical view of data validity

The observed U_{GD} histogram is compared to the modeled histogram.
→ They are **very similar in shape** but **offset.**



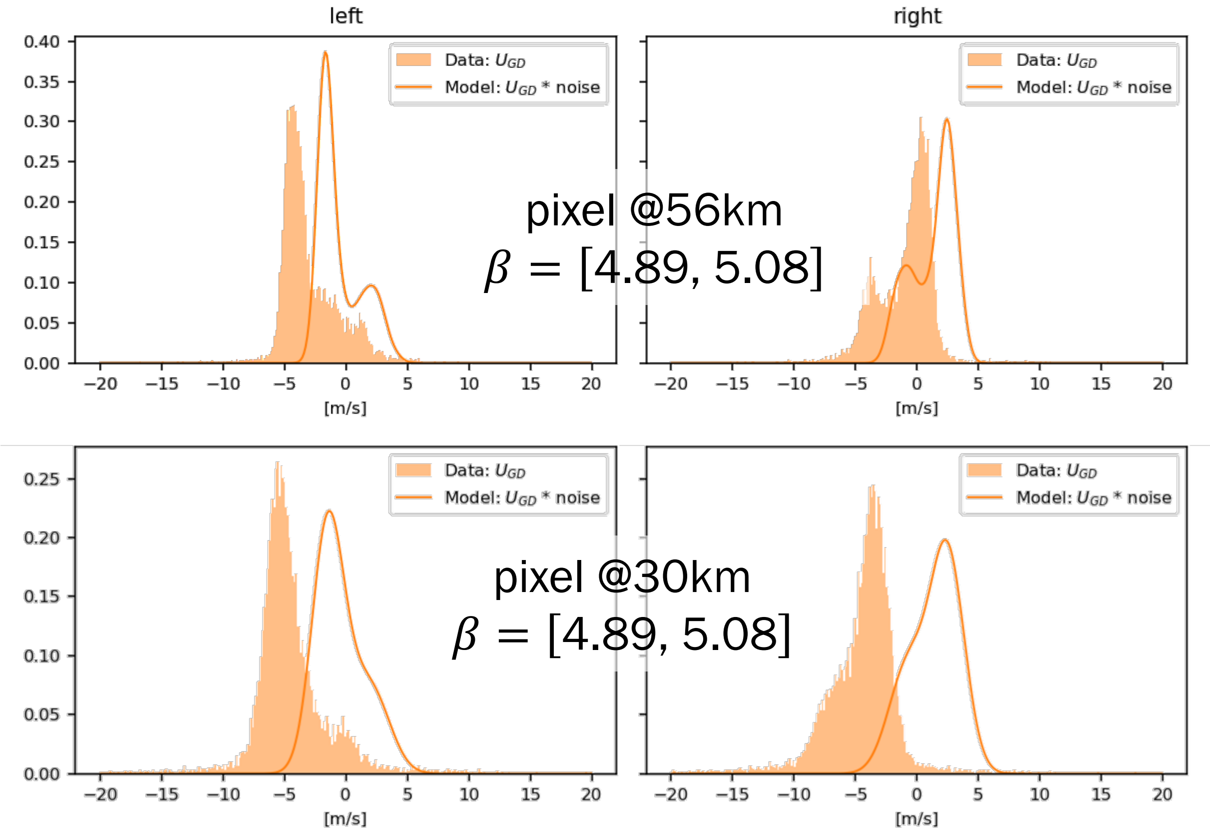
A statistical view of data validity

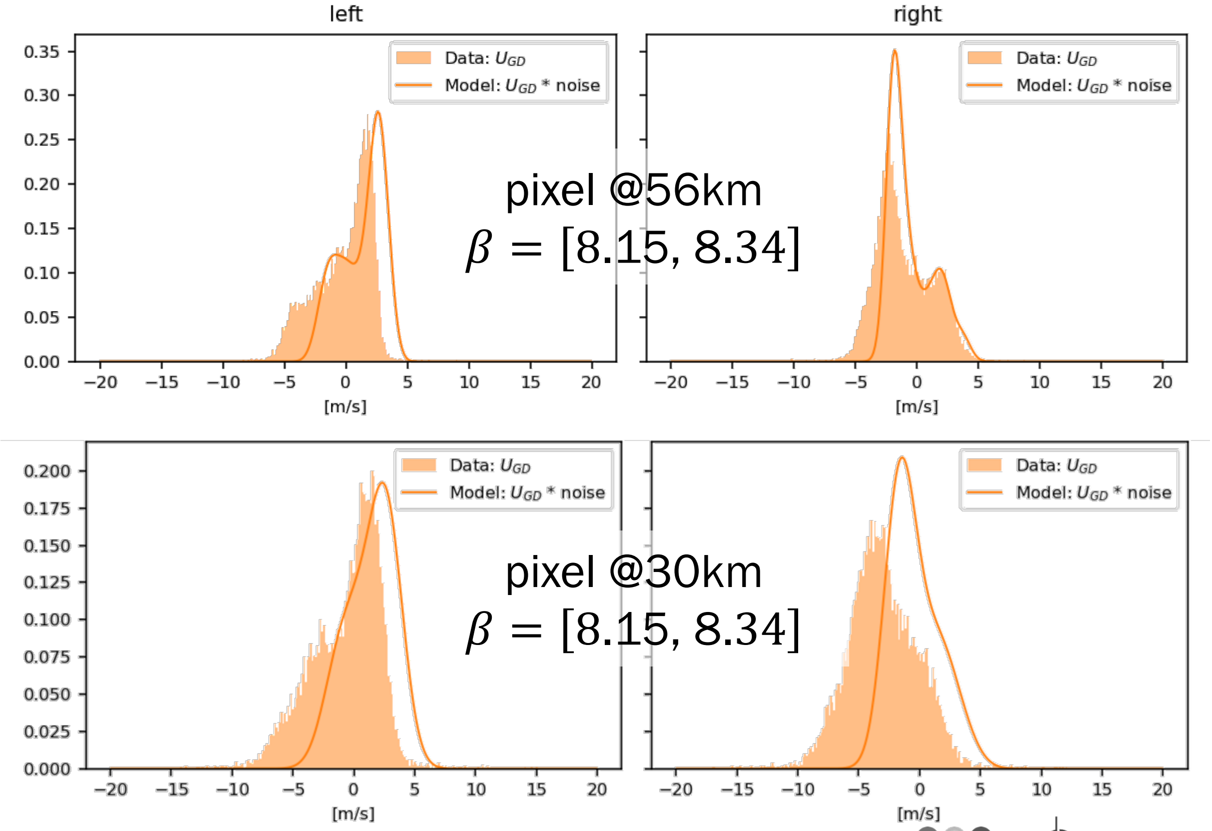
The conclusions remain valid for the other sets (pixel number, beta angle)

→ we are reasonably confident that the data does contain the geophysical signal, but it needs to be calibrated.

→ at given pixel number, the offset depends on the beta angle
→ at given pixel number, the offset depends on the swath/polarization

} the same dependencies will apply to the calibration





Need for Calibration: this was predictable

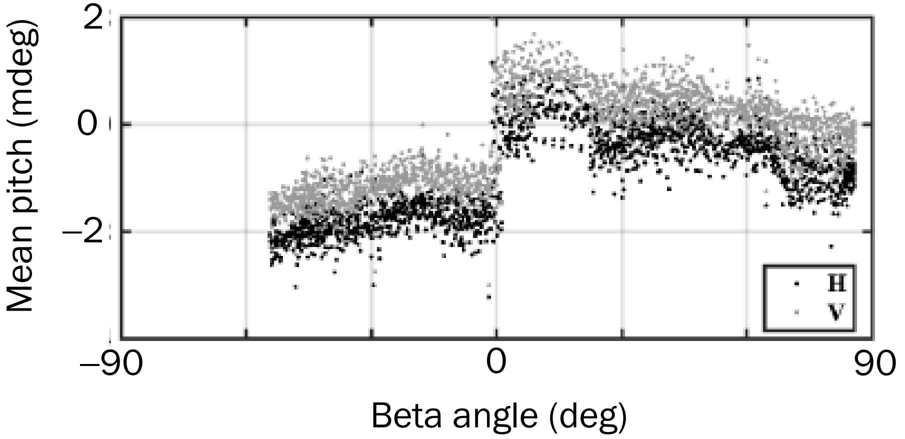
Geophysical Doppler = Measured Doppler – Non-Geophysical Doppler

originates from: The center of phase position in time + the ground projected antenna pattern shape.

There exists, for example, a **beta angle and polarization** dependency of the antenna pattern attitude w.r.t the platform.

These dynamic variations (in particular, in antenna pitch) at beta scale are not caught by Attitude Reconstruction.
⟶ some calibration is needed and is currently under construction.
⟶ results hereafter are calibrated with a preliminary version of the calibration

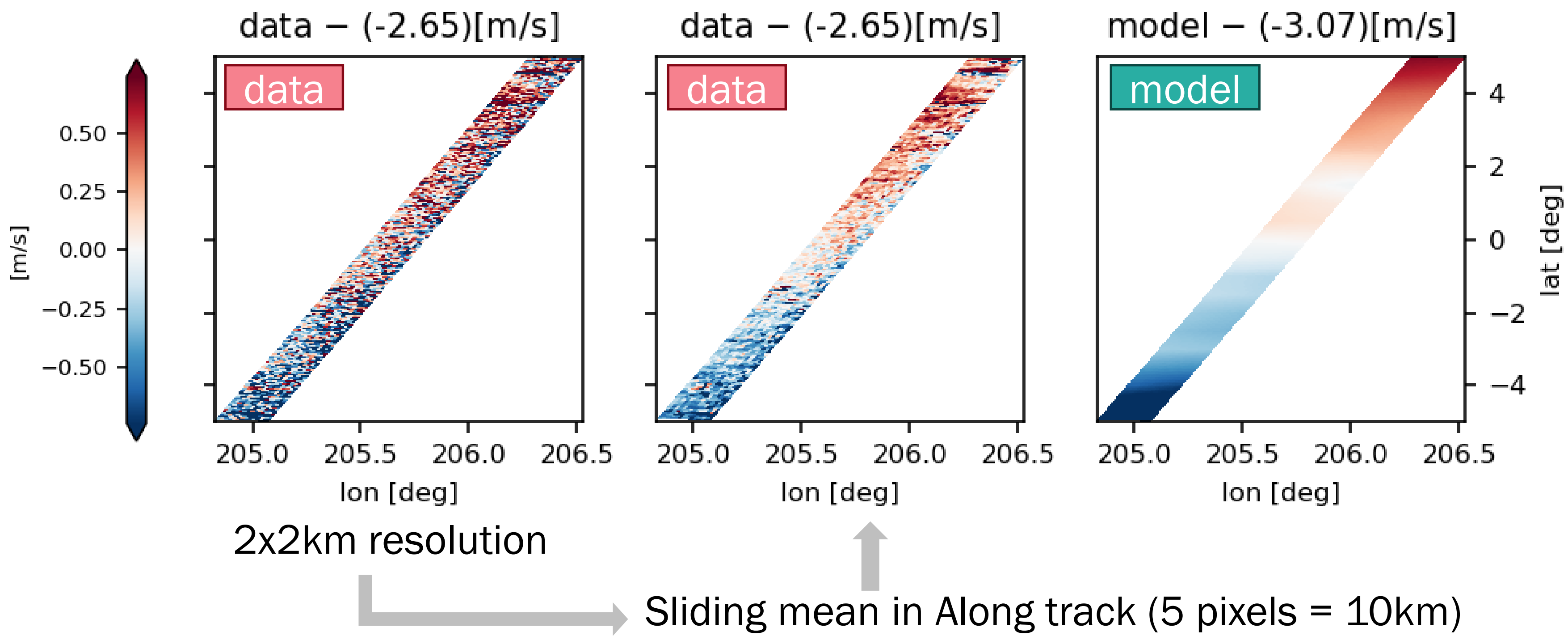
[Peral et al. 2024]



A mapped view of data validity: total geophysical current $U_{GD} = U_c^{\text{proj}} + U_{WD}$

Following results are preliminary results, under consolidation.

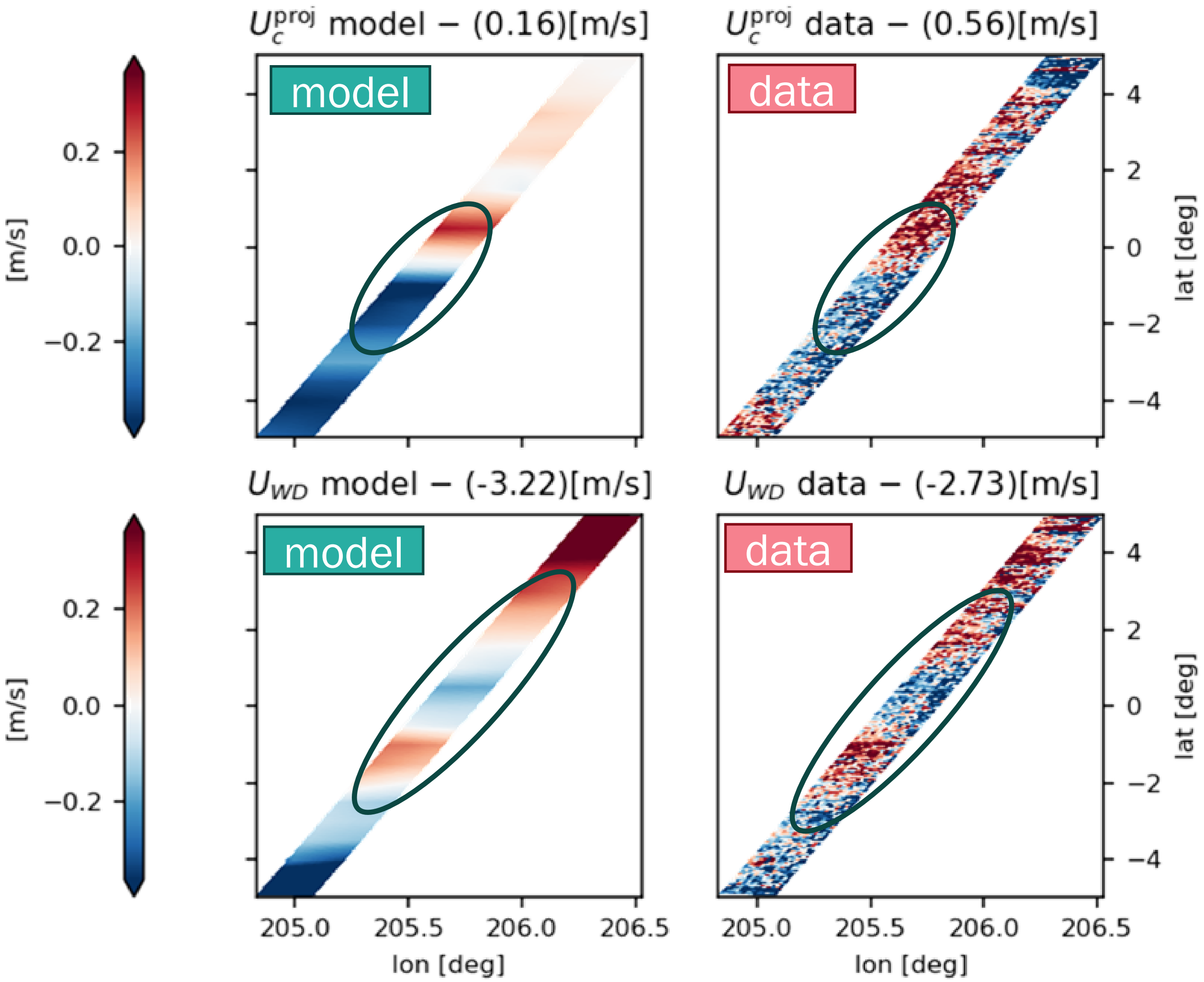
The median of all datasets is removed: medians do not match (diff of 0.5m/s), calibration to be improved, on going work + models can also be wrong



Cycle 32 pass 291
2025/05/08, 10am
Left swath: 30-56km
calibrated

The overall dynamic seen from the model is also observed in the data.

A mapped view of data validity: isolating U_c^{proj} and waves U_{WD} contributions



The median of all datasets is removed (and reported in titles)
Sliding mean in Along track (5 pixels). Left swath: 30-56km

We isolate the surface currents contribution assuming that the model for U_{WD} is perfect

$$U_c^{\mathrm{proj}}\mathrm{data} = (U_{GD}\ \mathrm{data}) - (U_{WD}\mathrm{model})$$

We isolate the waves contribution assuming that the model for U_c^{proj} is perfect

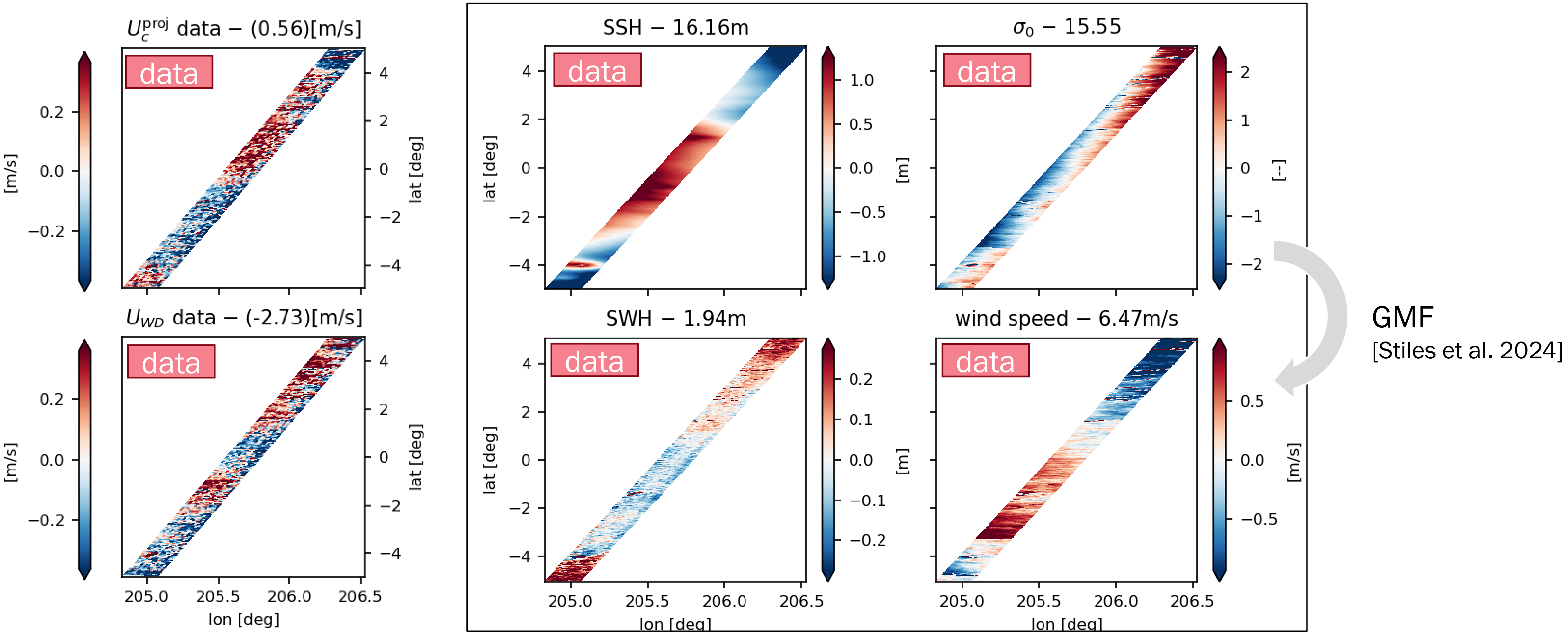
$$(U_{WD}\mathrm{data}) = (U_{GD}\ \mathrm{data}) - \left(U_c^{\mathrm{proj}}\mathrm{model}\right)$$

Some of the features and dynamics can be seen, with obviously some room for improvement.

Complementary information to topography ?

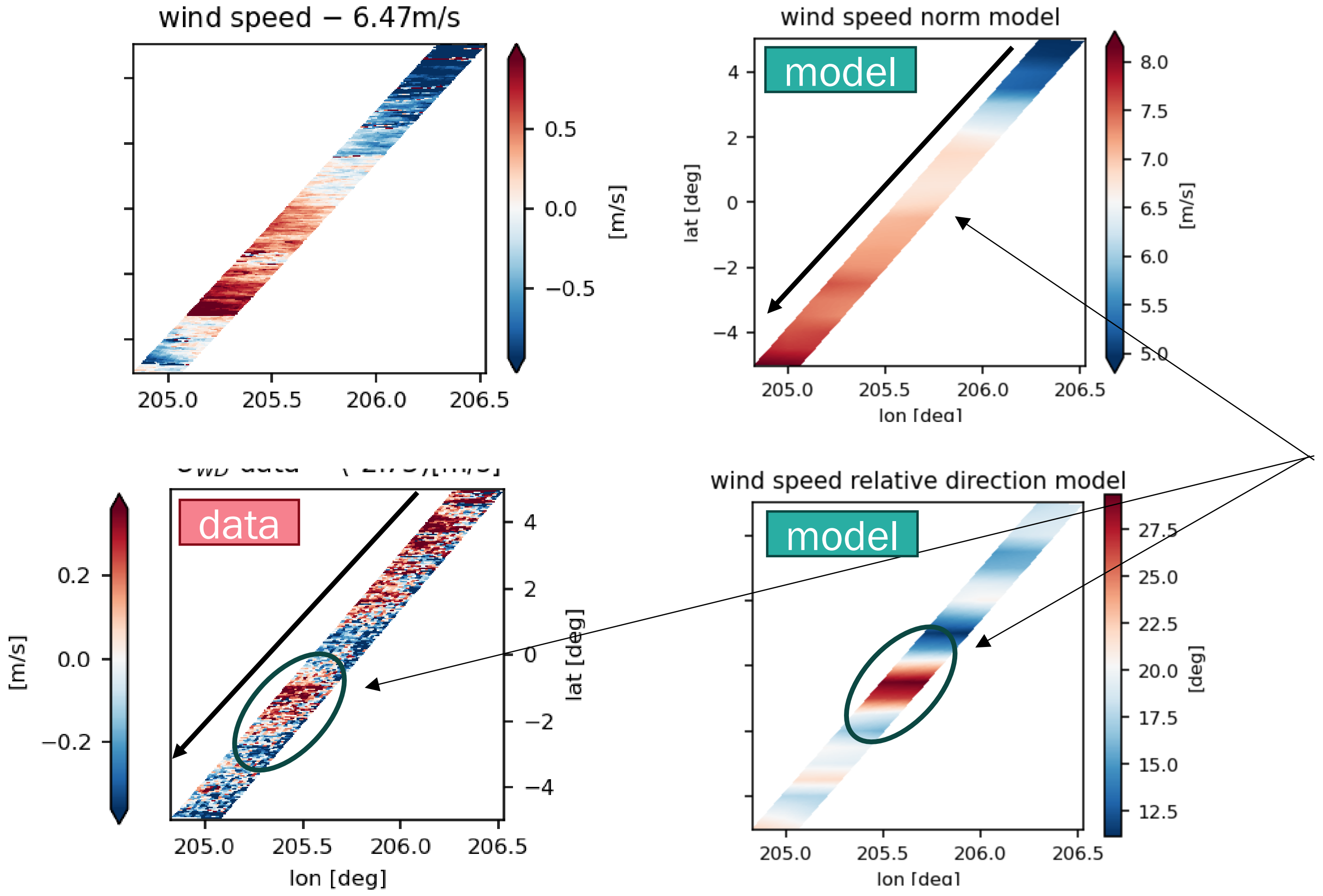
The median of all datasets is removed (and reported in titles) Left swath: 30-56km

KaRIn estimates @2x2km resolution



Nicely, the SWOT mission provides a set of spatially and temporally co-located geophysical estimates.

Complementary information to topography ?



U_{WD} is controlled to first order by the wind vector. The observed patterns do not match those of wind speed (neither measured nor model), because they also reflect local changes in the wind direction.

U_{WD} follows the linear trend of wind speed norm and also shows the local change of wind direction.

→ U_{WD} provides additional information to wind speed norm estimated from σ_0, related to the direction
→ next step of the study will consider how to take benefit of this additional information

Conclusions & outlook

- We showed some first evidence of the presence of a geophysical signal;
  - noisy, at highest resolution (2x2 km) but spatial averaging reveals structures
- Waves and currents contributions could be isolated, with support of models
  - Wave Doppler modelling : existing models [Nouguier et al. 2018] apparently supported by SWOT data.
  - WW3 inputs to modelling [Ardhuin, LOPS],
- to date, only a few isolated maps have been studied
  - calibration to be constructed
  - global assessment to be done
- The question of how this could be used to mitigate SSH measurements remains open.

<u>Data availability</u>

- L2_LR_Unsmoothed data product, variables:
  - *geophysical_doppler_miti*
  - *surface_velocity_doppler_miti*
- version D
  - Processing since cycle:32 / pass:223, 2025-05-06 + reprocessing
- Total Geophysical Velocities $\left(= U_{\mathrm{WD}} + U_c^{\mathrm{radial}}\right)$, **contributions not isolated.**
- **Not calibrated yet**

Backup slides

Bibliography

Boisot et al. (2016). *Dynamical Properties of Sea Surface Microwave Backscatter at Low-Incidence: Correlation Time and Doppler Shift*. IEEE Transactions on Geoscience and Remote Sensing, 54 , 7385-7395. doi: 10.1109/TGRS.2016.2601242

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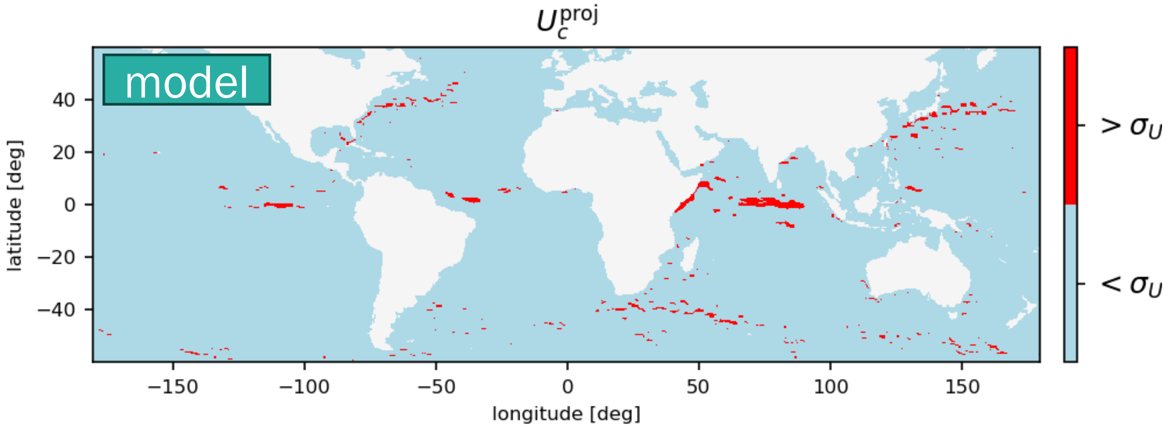
SWOT and some recent Doppler scatterometers mission concepts

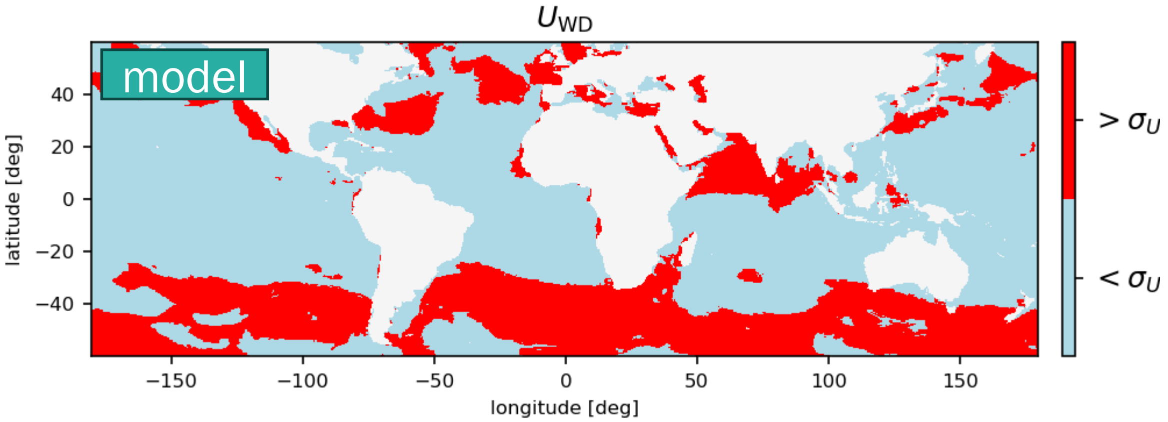
	SKIM	ODYSEA	SWOT
Agency	ESA Finalist of Earth Explorer 9 (2019)	NASA/CNES Competing in JPL Earth System Explorers Program (end-2025)	**NASA/CNES**
Objectives	Surface currents		**Sea state complementary information**
Geometry	Rotating antenna: several radial estimates for vector reconstruction		**Cross track (left & right) looking: radial estimate**
Incidences	6° & 12°	60° very wide swath → global daily revisit	**1° to 5°**
Radar band	**Ka Band**		

→ Models developed for SKIM are applicable to the SWOT context: Ka Band, Near Nadir

Will the signal exceed the noise in the data ?

At the highest resolution 2x2km

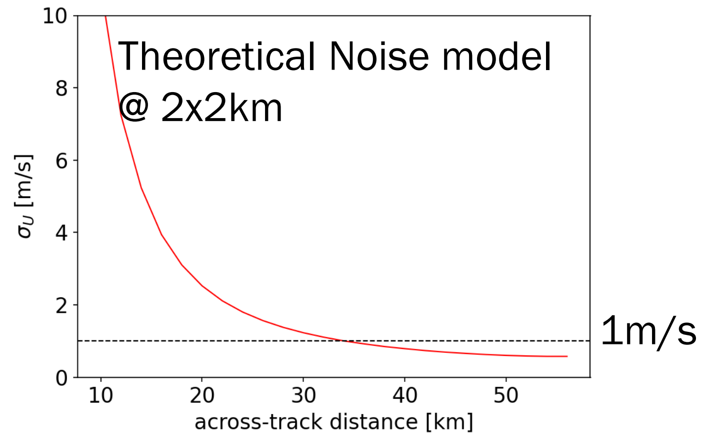




In red, locations where Signal-to-Noise-Ratio >1

<u>left panel</u>: signal is U_c^{proj}

<u>right panel</u>: signal is U_{WD}

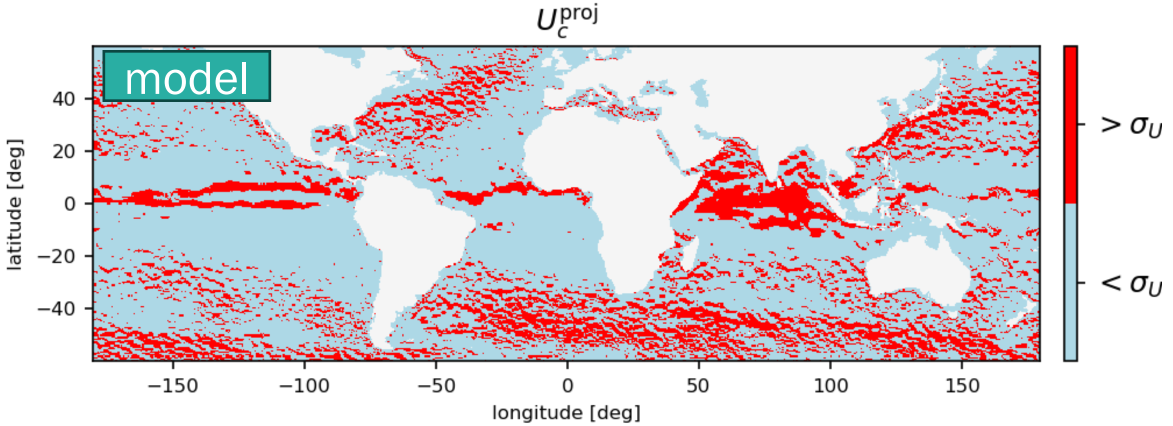


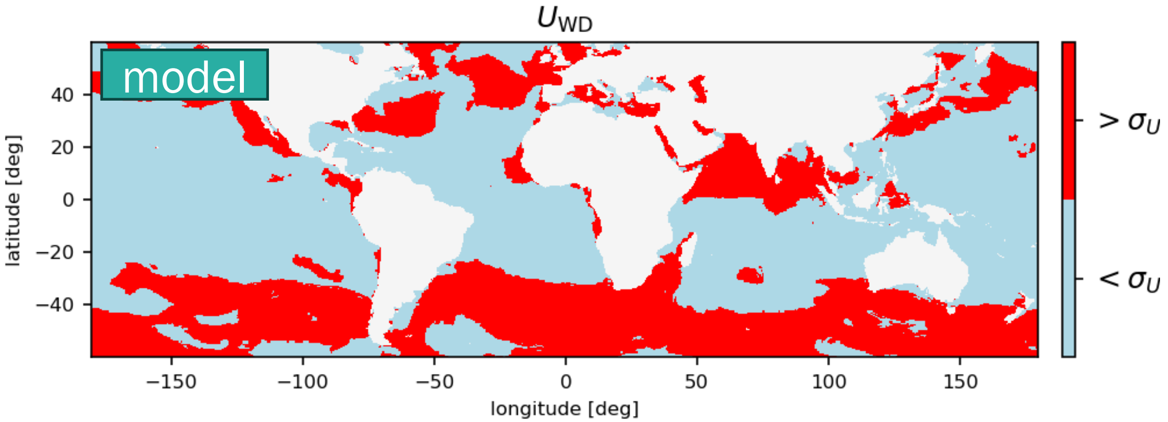
Standard deviation of the projected estimated velocities

If we assume that the 2 components of the Geophysical velocity can be isolated, the red locations shows where the U_c^{proj} and U_{WD} can be exploited.

Will the signal exceed the noise in the data .

Degraded resolution 10x10km





In red, locations where Signal-to-Noise-Ratio >1

<u>left panel</u>: signal is U_c^{proj}

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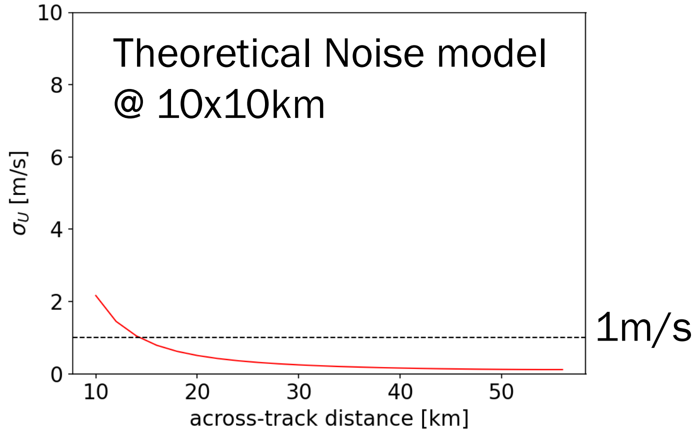
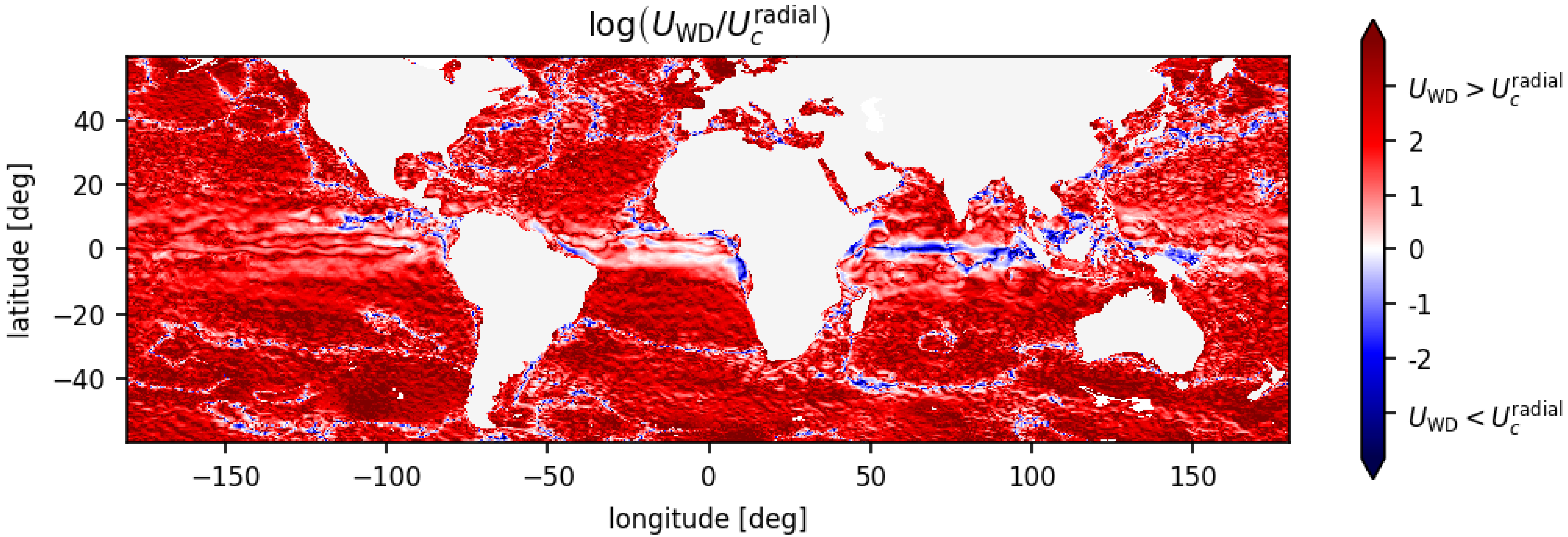


Standard deviation of the projected estimated velocities

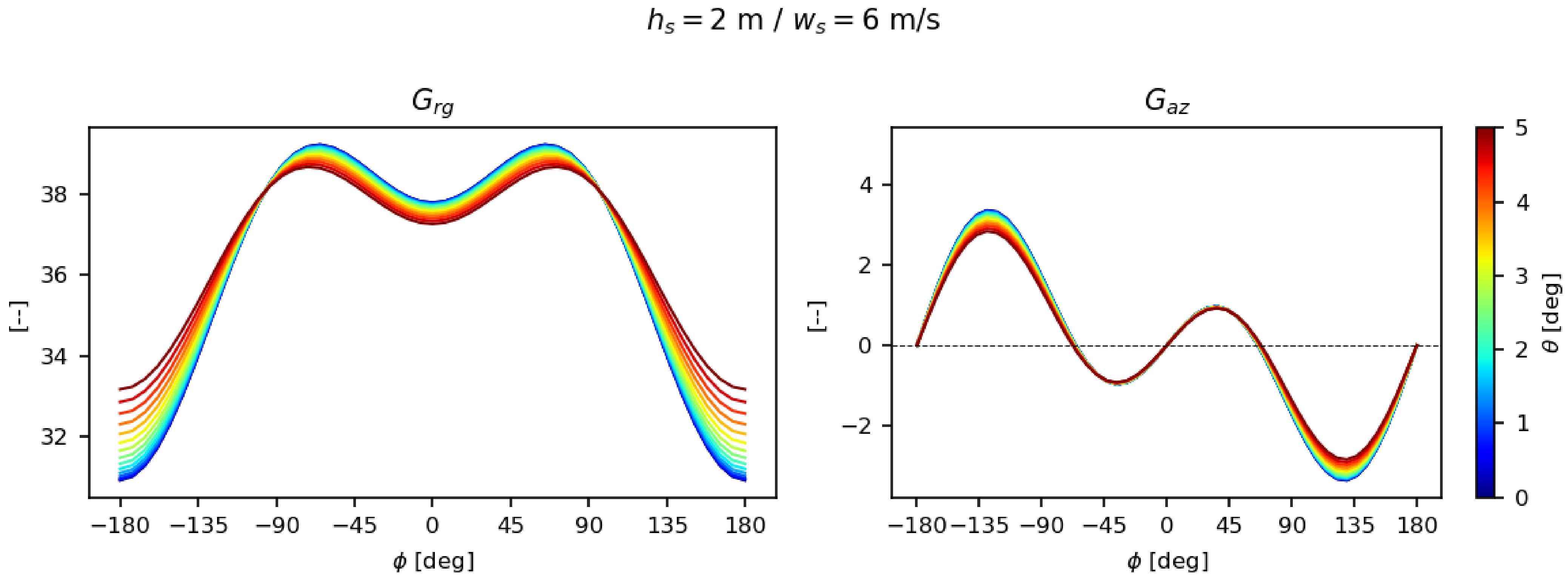
Where is the surface current signal bigger than the wave signal ?



- In blue the surface currents are bigger than the wave signal
- In red the wave signal is bigger than the surface currents

Gain factor

The non-dimensional gain factor **G** has been derived with the use of Global Precipitation Measurement (JAXA/NASA) datasets,



The SWOT Doppler measurements.

2 Doppler estimates in SWOT

- The SSH estimation process includes a Doppler centroid estimation
  - performed on-board on the raw data
  - used during the on-board azimuth compression to re-center the Doppler spectrum approximately at 0Hz.
  - meant to maximize SNR which relates to SSH noise minimization
  - linear fit in across track direction, every 25km in along-track

- **2-D Mitigation/ "High Resolution" Doppler image:**
  - estimated on board, using a pulse pair algorithm on the range compressed data (yet, before the azimuth compression on-board algorithm), for one channel only.
  - The mitigation Doppler data product has been designed as an **additional product** with potential use in improving the SSH data product, by means of **sea state characterization**
  - 2x2-km resolution and 2x2-km posting: pixels centered from 10km to 56km for a total of 24 pixels.