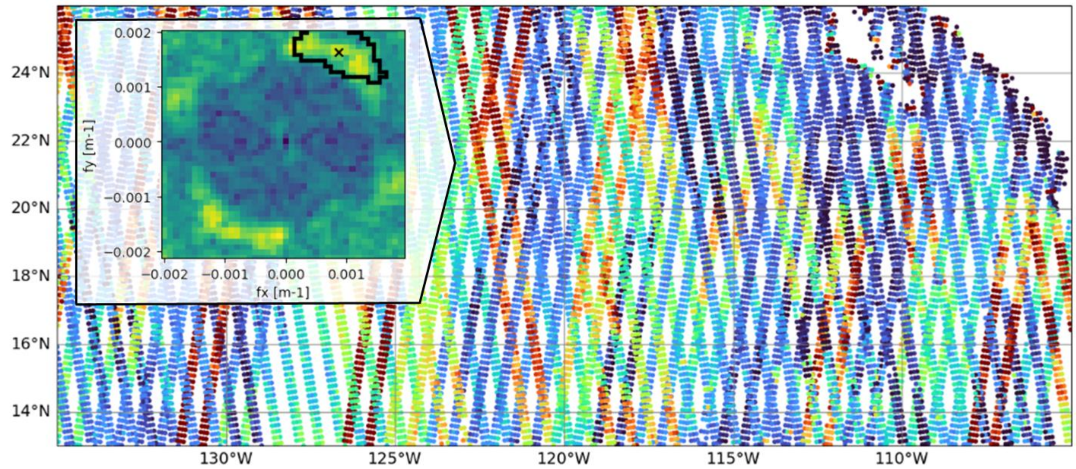
DUACS Level-3 SWOT KaRIn (L3_LR_WIND_WAVE) User Handbook



Nomenclature: SALP-MU-P-EA-23689-CLS

Issue:1.0

Date: March 2025

Chronology Issues:			
Issue:	Date:	Validated by	Reason for change:
1.0	March 2025		First version

List of Acronyms

AVISO	Archiving, Validation and Interpretation of Satellite Oceanographic data
CLS	Collecte, Localisation, Satellites
CNES	Centre National d'Etudes Spatiales
FFT	Fast Fourier Transform
L2	Level-2 product
L3	Level-3 product
PSD	Power spectral density
SSH	Sea surface height
SSHA	Sea surface height anomaly
SWH	Significant wave height

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1 Introduction

This user manual describes the products named “SWOT L3 KaRIn Wind Wave”. These products are funded by CNES and are formally part of the SWOT Science Team projects VAGUES and DESMOS, also funded by CNES.

The SWOT KaRIn Level-3 Wind Wave product (L3_LR_WIND_WAVE) is an innovative product derived from the Unsmoothed L3_LR_SSH product (https://doi.org/10.24400/527896/a01-2024.003) and based on the algorithm presented in Ardhuin et al. (2024), using both sea surface height (SSH) and the normalized radar backscatter (NRCS). It takes advantage of the capability of the KaRIn Low Rate (LR) chain of resolving waves greater than ~500 m in wavelength (~18 s) with a very high precision (few centimeters). The basic geophysical quantity contained in this product is the wave spectrum, which can be directly compared to other estimates of the wave spectrum from in-situ buoys, SAR-based systems and SWIM on CFOSAT, or numerical wave models. The particularity of the SWOT KaRIn LR data is that it only resolves long waves, and thus the spectrum is limited to wavelengths greater than 500 m. Although these long waves are infrequent in the open ocean and completely absent in marginal seas, they are related to the most severe ocean storms and have important consequences on coastal dynamics (generation of infragravity waves, harbor agitation, coastal flooding...) and are an interesting source of signal for seismology. Also, the high precision of SWOT measurements makes it possible to use SWOT to calibrate other sensors (such as SWIM and Sentinel-1 SAR) that use empirical modulation transfer functions (MTF) or neural networks for relating radar modulation amplitudes to actual wave amplitudes. Understanding wave properties is essential for improving wave forecasting models, assessing their impact on coastal infrastructures, and advancing studies in ocean-atmosphere interactions and seismology.

The full wave spectrum can also be “partitioned” in swell components for which a height, wavelength and direction can be estimated.

Two types of files are distributed: Light and Extended.

The Light (or lightweight) L3_LR_WIND_WAVE includes two-dimensional (2D) power spectral density (PSD) estimates of SWOT KaRIn 250-m sea surface height anomaly (SSHA), a mask identifying swell energy in the spectra and derived wave parameters (Significant Wave Height, wavelength and direction). The PSD are estimated over 40 km by 40 km samples (“boxes”) of SSHA using a 2D fast Fourier transform (FFT) Welch (1967) approach on tiles of 5 by 5 km, following the approach in Ardhuin et al., (2024). This was optimized to produce the smallest possible file size, and lowest possible noise level by averaging many tiles (64 independent tiles give 128 degrees of freedom and a sampling uncertainty of a few percent only): this will probably be most useful for large scale swell field investigations, and the detection of weak swell signals (scattering by islands and underwater bathymetry, reflections of land and ice...).

The Extended L3_LR_WIND_WAVE includes the variables of the Light product plus variables related to instrumental corrections and the wave model used in the algorithmic core. The main added value of the extended product lies in the various box size/tile size configurations:

- 40 km boxes with 5 km tiles (Light product)
- 40 km boxes with 10 km tiles
- 20 km boxes with 10 km tiles
- 10 km boxes with 5 km tiles

And additional variables:

- Phase of the cross-spectrum between SSH and NRCS (useful for removing 180° wave propagation ambiguity)
- Coherence of SSH and NRCS spectra
- Real part of SSH-NRCS cross-spectrum

Publications should include the following statement in the Acknowledgments:

Citation Light L3_LR_WIND_WAVE:

"The SWOT_L3_LR_WIND_WAVE product, derived from the SWOT_L3_LR_SSH product, is produced and made freely available by AVISO, DUACS and LOPS teams as part of the DESMOS and VAGUES Science Team projects".
AVISO/DUACS., 2025. SWOT Level-3 KaRIn Wind Wave (v2.0) [Data set]. CNES. https://doi.org/10.24400/527896/a01-2024.016

Ardhuin, F., Molero, B., Bohé, A., Nouguier, F., Collard, F., Houghton, I., et al.(2024). Phase-resolved swells across ocean basins in SWOT altimetry data: Revealing centimeter-scale wave heights including coastal reflection. Geophysical Research Letters, 51, e2024GL109658. https://doi.org/10.1029/2024GL109658

Citation Extended L3_LR_WIND_WAVE:

"The Extended SWOT_L3_LR_WIND_WAVE product, derived from the SWOT_L3_LR_SSH product, is produced and made freely available by AVISO, DUACS and LOPS teams as part of the DESMOS and VAGUES Science Team projects".
AVISO/DUACS., 2025. SWOT Level-3 KaRIn Wind Wave Extended (v2.0) [Data set]. CNES. https://doi.org/10.24400/527896/a01-2024.017

Ardhuin, F., Molero, B., Bohé, A., Nouguier, F., Collard, F., Houghton, I., et al.(2024). Phase-resolved swells across ocean basins in SWOT altimetry data: Revealing centimeter-scale wave heights including coastal reflection. Geophysical Research Letters, 51, e2024GL109658. https://doi.org/10.1029/2024GL109658

1.1 Data Policy and conditions of use

The SWOT Level-3 KaRIn Wind Wave ocean product is available free of charge for scientific studies and commercial activities, and distributed by AVISO under standard AVISO+ license agreement.

2 Processing

This section describes the processing of the SWOT L3 WIND WAVE KaRIn (L3_LR_WIND_WAVE) product.

2.1 Input data

The input data used to compute the 2D KaRIn SSHA spectra contained in the L3 WIND WAVE products are the Unsmoothed SWOT_L3_LR SSHA, defined with a ~250x250 m spatial posting interval and distributed by AVISO (https://doi.org/10.24400/527896/a01-2023.015). Currently, SSHA with quality flag #0 (good), #10 (coast) and #20 (sea ice) are selected.

To infer wave characteristics from the KaRIn SSHA spectrum, it is essential to distinguish wind sea and swell from other signals in the L3 SSHA spectrum (essentially instrumental effects, but also internal waves, sea ice features ...). In general, these other signals have different spectral components, and we have used a mask to identify the region of the spectrum that we believe is dominated by surface gravity waves. In this version of the product, the mask is computed from a numerical wave model (Ardhuin, F. and M. Accensi, 2024).

The model is also used to estimate the expected root mean square orbital velocity of waves w_{rms} which gives an estimate of the radar azimuthal cut-off. Random wave velocities along the line of sight of the radar leads to a loss in resolution in the azimuth direction, represented by an exponential term $\exp(-f_y\, \lambda_c)$ with λ_c the azimuthal cut-off. Although well documented for NRCS in SAR systems, the direct application of such an equation for the coherence phase of an inSAR system such as KaRIn is still under investigation.

The model version used employs the T707GQM configuration, as described in Alday and Ardhuin (2023), and has been extensively validated using satellite altimeter data and *in situ* buoy measurements. It operates at a spatial resolution of 0.5° by 0.5°, with a 15° angular resolution and exponentially spaced discrete frequencies, featuring a relative increment of 1.1 between consecutive frequencies. Two key features make this model unique: it accounts for coastal reflection, and it incorporates a GQM-based non-linear interaction term (Lavrenov 2001).

Table 1 lists the product versions used in the L3 WIND WAVE production.

	L3 WW SWOT-KaRIn v2.0
SSHA product	SWOT_L3_LR_SSH unsmoothed v1.0.2
Ancillary wave model	WAVEWATCH III model results (Ardhuin & Accensi 2024)

Table 1: Product versions used in the L3 WIND WAVE KaRIn production

2.2 Spatial sampling and resolution

The SSHA PSD are estimated over a square region (“box”) in the SWOT swath of length L_{box}, by using a 2D fast Fourier transform (FFT) Welch (1967) approach on tiles of length L_{tile}. As introduced above, different combinations of L_{box} and L_{tiles} are possible in the Extended product, which should give the user the freedom to choose among a variety of spectral estimations with different noise and resolution properties. As L_{box} increases, the variance of the spectral estimation is reduced but the probability of geophysical heterogeneity within the box increases. As the tile size, as L_{tile} increases, bigger wavelengths can be resolved, and the spectral resolution becomes finer, but the spectral estimation variance increases as well.

Following Ardhuin et al. (2024), we have chosen a baseline box size of 40 by 40 km, which is about 160 cross-track pixels and 168 along-track pixels (the average LR-unsmoothed resolution is around 235 m, JPL 2021), centered in the middle of each left and right swaths. In the Light L3 WIND WAVE product, the tile size is set to 5 km, which allows to have a good restitution of the smallest wavelengths ($\leq 1\ km$).

This means that the Light L3 WIND WAVE product provides one SSHA spectrum -and derived wave parameters- per left/right swath and every 40 km in along-track, as represented by the green boxes in Figure 1.

The 40 km box defines the along-track and across-track sampling of L3 WIND WAVE variables, even in the case of the Expert product where other combinations of box and tile size are present (40/10 km, 20/10 km, 10/5 km). For example, in the case of the 20 km box, 6 boxes of 20 km are defined as nested inside each 40 km box, i.e., there are 6 boxes of 20 km for each along-track position (Figure 1, orange boxes).

For each resolution, a 50% overlap is applied in the cross-track direction, as illustrated in Figure 1. In this version, no overlap is implemented in the along-track direction.

As a result, with 20 km boxes, there are 3 boxes in cross-track and 2 boxes in along-track, spaced every 84 pixels along the track, corresponding to approximately 20 km. The 10 km by 10 km boxes, shown in purple in Figure 1, feature seven boxes in cross-track and 4 boxes in along-track, spaced every 42 pixels along the track, equivalent to roughly 10 km.

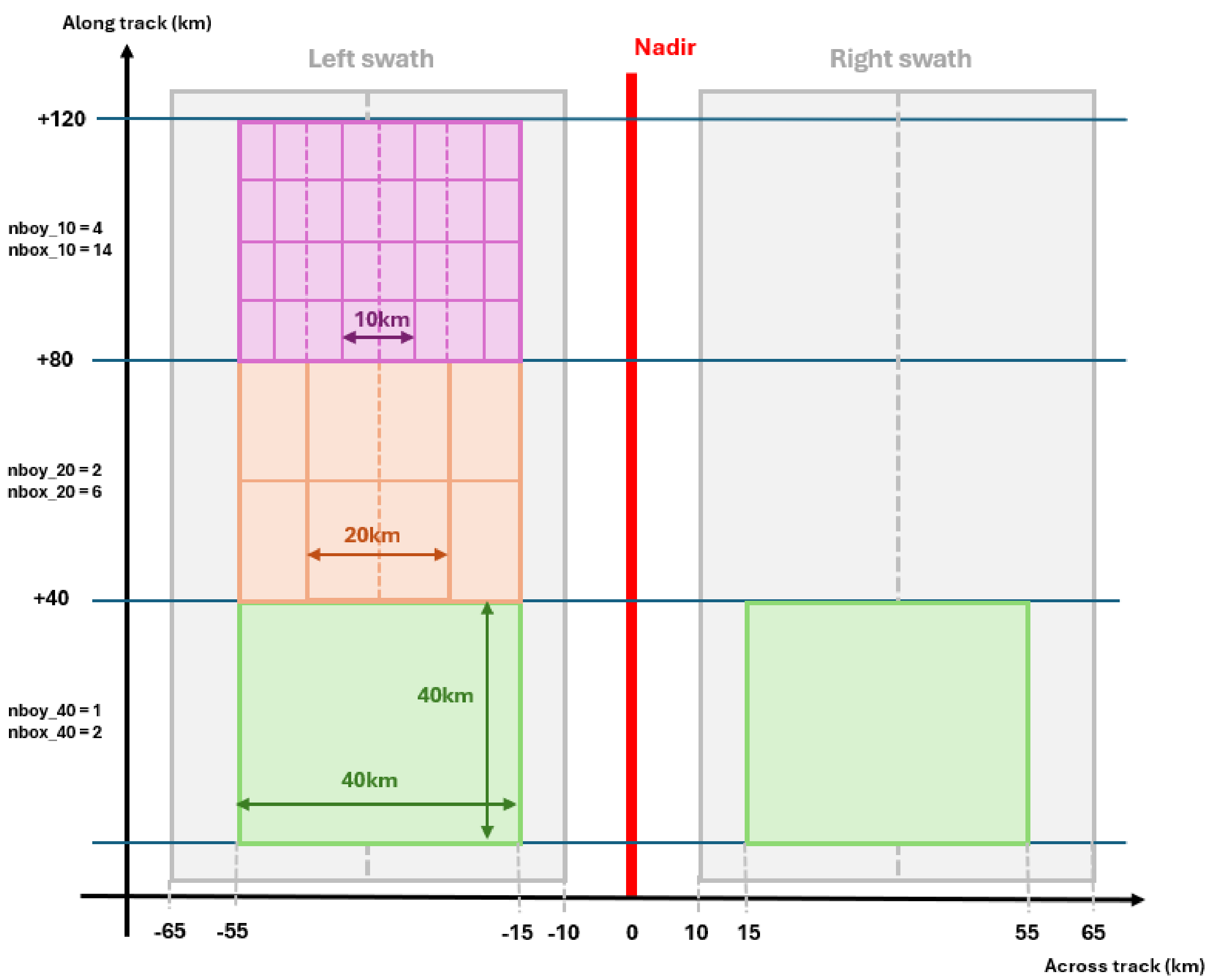

Figure 1 Schematic representation of the different spectral resolutions within the SWOT swath

In the extended products, the variables box_indx and box_indy are provided to locate the position of each box within the swath, corresponding to the cross-track and along-track directions, respectively. As shown in Figure 1, the box_indx values are defined as follows:

- **0-1** for 40 km boxes (left or right swath)
- **0-5** for 20 km boxes (0-2 for the left swath and 3-5 for the right swath in the satellite frame)
- **0-13** for 10 km boxes (0–6 for the left swath and 7–13 for the right swath in the satellite frame).

2.3 Wave spectrum estimation

This paragraph gives a complete description of the approach followed for computing SSHA-based wave spectra, for waves with periods longer than ~500 m (18 s). This limitation on wave period is due to Nyquist condition: unsmoothed KaRIn data has a spatial posting of ~250 m so the smallest observable wavelength is ~500 m, which is equivalent to ~18 s through the wave dispersion equation. For this reason, integrated wave parameters are denoted with the suffix "18" as H_{18} (significant wave height), L_{18} (wavelength) and ϕ_{18} (wave direction).

The estimation of the wave heights PSD starts with the computation of the KaRIn SSHA power spectral density, $E_s(f_x, f_y)$, using a two-dimensional Welch (1967) method as described in Ardhuin et al. 2024. The estimation is performed for each spatial box described in Section 2.2. Each box is subdivided into multiple individual tiles of specific dimensions, with a 50% overlap applied in both directions.

The frequencies f_x and f_y are the inverse of the distance in cross-track direction ("x") and along-track direction ("y") with respect to the satellite. The cross-track distance x is defined increasing towards the right swath (Figure 2).

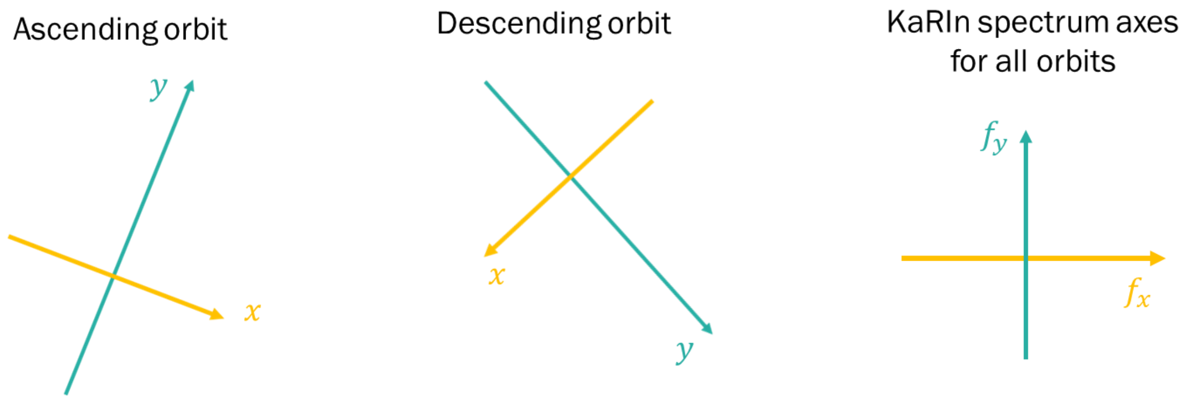

Figure 2 - KaRIn coordinate system

Then, the KaRIn SSHA power spectral density, $E_s(f_x, f_y)$, is corrected by an approximation of the KaRIn transfer function $G(f_x, f_y)$, which accounts mainly for the azimuth point target response (PTR) and the filters used on-board to reduce the sampling rate to 250 m (Ardhuin et al. 2024):

$$E(f_x, f_y) = E_s(f, f_y)/G(f_x, f_y)$$

<u>Note that $G(f_x, f_y)$ does not take aliasing into account.</u>

Finally, regions of the $E(f_x, f_y)$ spectrum containing swell energy are identified and the so called "swell mask" is provided together with the corrected spectrum.

2.4 Definition of the swell mask

Different approaches to identify the swell energy in the KaRIn SSHA spectrum are under investigation. KaRIn SSHA spectra can be noisy, which complexifies the detection of energy clusters in the spectrum. The correlation between sigma0 and SSHA can be exploited as in Ardhuin et al. 2024, but it fails to detect very long swells with low Hs (Husson et al. 2024). Probably, the obtention of a swell mask would require a combination of approaches. In the meanwhile, in this version, we rely on a simple method based on energy clustering of the WW3 wave model. Wave model spectra have the advantage of not presenting spectral noise, which eases the energy clustering.

For each SSHA box, the closest WW3 wave spectrum in time and space is selected. The WW3 spectrum is then:

1) re-interpolated from its frequency grid in polar coordinates to the KaRIn frequency grid in cartesian coordinates. KaRIn frequency axes, fx and fy, refer to across-track and along-track distances, while the WW3 grid is orientated following a meteorological North-East convention. The re-interpolation from polar to KaRIn cartesian coordinates includes a rotation of the angle coordinate in accordance with the SWOT track angle.
2) multiplied by an approximation of the KaRIn transfer function that includes the azimuth PTR, the on-board averaging filters and the azimuth cutoff effect

The swell mask is computed on this transformed WW3 spectrum. The current algorithm works as follows:

- selects pixels of the spectrum whose power is higher than one fourth of the maximum power
- through a binary dilation algorithm, detects the clusters of energy among those pixels
- detects the maximum value within the clusters and its frequency f_{maxval}
- discards pixels falling in frequencies such as $f > 2f_{maxval}$ and $f < 0.6f_{maxval}$

The current swell mask algorithm can detect separated energy clusters in the spectrum, revealing different probable swell regimes.

2.5 Computation of swell parameters

The wave parameters significant wave height (H_{18}), wavelength (L_{18}) and direction (ϕ_{18}) are computed using the values of the KaRIn SSHA spectrum identified as swell energy by the swell mask as follows:

$$H_{18} = 4\sqrt{\sum_{f_x,f_y \in swell\ mask} E(f_x, f_y)}$$

$$L_{18} = \frac{\sum_{f_x,f_y \in swell\ mask} E(f_x, f_y) \frac{1}{\sqrt{f_x^2 + f_y^2}}}{\sum_{f_x,f_y \in swell\ mask} E(f_x, f_y)}$$

$$\phi_{18,SWOT} = arctan2\left(\sum_{f_x,f_y \in swell\ mask} \frac{f_x\, E(f_x, f_y)}{N}, \sum_{f_x,f_y \in swell\ mask} \frac{f_y\, E(f_x, f_y)}{N}\right)$$

with $E(f_x, f_y)$ the KaRIn SSHA spectrum corrected for KaRIn transfer function and N the number of pixels within the swell mask.

The value L_{18} can be smaller than 500 m. For swells travelling in cross-track direction with respect to the satellite, the smallest visible wavelength is 500 m because the cross-track sampling is 250 m. However, the highest visible frequency in the two-dimensional spectrum is not $f_s/2$ but $\sqrt{2}f_s/2$, which gives wavelengths that can go down to ~342 m if we consider that the along-track sampling is closer to 235 m than to 250 m (JPL, 2021).

The swell direction is initially computed in the SWOT coordinate system as $\phi_{18,SWOT}$ (across-track frequencies f_x, along-track frequencies f_y) but is then translated into the classical meteorological North-East system:

$$\phi_{18} = \phi_{18,SWOT} + track\ angle$$

Finally, it should be noted that the wave parameters are computed over the spectrum pixels identified as swells, no matter if they belong to different separate swell regimes or not. For this reason, the swell wavelength L_{18} can be seen as the equivalent mean wavelength of all the swell regimes present in the scene, and a similar interpretation applies to ϕ_{18}.

2.6 Quality flag

The L3 WIND WAVE product v2.0 provides a quality flag. The flag is bitwise, and different bits can be set to 1 for the same pixel, allowing to express more than one information.

- Flag value 0 (no bits set to 1)**: Good** data.
- Flag value 2 (bit #1): **Suspect** ratio of energy between swell masked region and whole spectrum

  The ratio between twice the energy contained in the swell mask and the total energy of the SSHA spectrum E(f_x,f_y) is below a certain threshold, set to 50% in this version (see Figure 3).

- Flag value 4 (bit #2): **Suspect** number of tiles used for FFT computation.

  The number of tiles used in the FFT computation is too low compared to the expected number of tiles. This flag is typically raised in coastal areas where boxes overlap the land/sea interface. The threshold for the percentage of usable tiles is set at 25%.

- Flag value 8 (bit #3): **Suspect** separated swell mask clusters.

  The swell mask computed from the WW3 model spectrum shows separated energy clusters. This may indicate the presence of multiple wave regimes or a misidentification in the mask detection process (see Figure 4). Therefore, in this case, L_{18} and ϕ_{18} are the equivalent mean wavelength and mean direction of all the swell systems identified in the SSHA spectrum.

- Flag value 16 (bit #4): **Suspect** H18 estimation from WW3 model spectrum.
- H18 estimated from the masked part of the WW3 wave spectrum is very low and does not allow for a clear wave regime identification. This flag is often raised in enclosed seas or closed oceanic basins where sea state is dominated by wind wave regimes. The threshold over the minimum H18 value has been set to 0.01m in this version.Flag value 4096 (bit #12): **Degraded** no matching WW3 model sample found.

  WW3-derived variables are missing in consequence, although the SWOT spectrum E(f_x,f_y) is still provided.

- Flag value 32768 (bit #15): **Bad** No SSHA values available.

  Related to missing input L3 SSHA data mostly.

The flag meanings are ordered following four states: **Good**, **Suspect**, **Degraded**, and **Bad**. We advise always using good pixels. Suspect pixels can be used with caution.

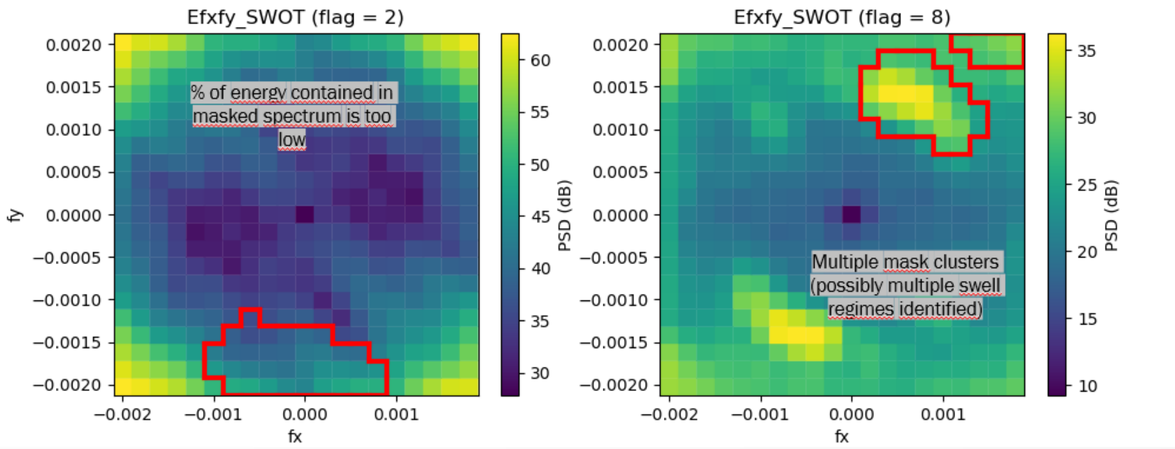

Figure 5: $E(f_x, f_y)$ and swell mask (delimited by red lines) for flag values 2 (left plot) and 8 (right plot)

3 SWOT L3 KaRIn (L3_LR_WIND_WAVE) Products

3.1 Temporal availability

Table 2 indicates the first and last dates available (and the corresponding cycle and track numbers).

	V2.0
1-day CalVal phase	-
21-day Science phase	C002/T001 – C016/T554 11th August 2023 - 17th June 2024

Table 2: Temporal availability of the SWOT L3 KaRIn WIND WAVE products

Some half orbits are missing due to the absence of input SSHA data.

3.2 List of variables

Name of variable	Signification	Unit
time	Time of measurement in seconds in the UTC time scale since 1 Jan 2000 00:00:00 UTC	s
longitude	Longitude	degrees East
latitude	Latitude	degrees North
track_angle	Angle between North and satellite flying direction	degrees
Efxfy_SWOT	PSD of KaRIn L3 250m SSHA corrected from instrumental effects	m^2.m^2
fx2D	Spatial frequency in cross-track direction	m^-1
fy2D	Spatial frequency in along-track direction	m^-1
swell_mask	Mask for wave energy inside Efxfy_SWOT	1
E_f_phi_SWOT_masked	Swell section of Efxfy_SWOT interpolated on polar nautical coordinates	m^2.m^2
f_vector	Spatial frequency vector for polar E_f_phi_SWOT_masked spectrum	m^-1
phi_vector	Phase vector for polar E_f_phi_SWOT_masked spectrum	rad
quality_flag	Quality flag (see section 2.6 for details)	-
Efxfy_model	WW3 wave model in SWOT cartesian frequency grid, symmetrized	m^2.m^2
H18	Significant wave height for waves longer than 18s (see section 2.52.6 for details)	meters
L18	Wavelength taken as the ratio of zeroth and first moment of the spectrum (m0/m1) (see section 2.5 for details)	meters
phi18	Swell propagation direction taken as the direction of the mean wavenumber vector (see section 2.5 for details)	degrees
H18_model	Significant wave height for waves longer than 18s, derived from the WW3 model	meters
L18_model	Wavelength taken as the ratio of zeroth and first moment of the spectrum (m0/m1), derived from the WW3 model	meters
phi18_model	Swell propagation direction taken as the direction of the mean wavenumber vector, derived from the WW3 model	degrees
sigma0_mean, sigma0_std	Mean and standard deviation of KaRIn backscatter	1
time_model	Time of matching WW3 data in the UTC time scale since 1 Jan 2000 00:00:00 UTC	s

longitude_model	Longitude of matching WW3 model data	degrees East
latitude_model	Latitude of matching WW3 model data	degrees North
index_model	WW3 model time index	1
Hs_model	WW3 model significant wave height	meters
lambdac_model	Radar azimuthal cutoff wavenumber from model parameters	m^-1
ang_SWOT	Mean phase shift between KaRIn SSHA and sigma0	rad
coherence_SWOT	Coherence between KaRIn SSHA and sigma0	1
crosr_SWOT	Real part of cross-spectrum between KaRIn SSHA and sigma0	m.m^2
filter_OBP	Instrumental filter, KaRIn OBP averaging function	m^2.m^2
filter_PTR	Instrumental filter, KaRIn azimuthal PTR function	m^2.m^2
box_indices	L3 SSHA pixel indices of the geographical box	1
box_indx, box_indy	Indexes locating the box along and cross track in the swath	1

Table 3: List of variables in the NetCDF files (the variables in the blue lines are in Extended files only)

3.3 Nomenclature of files

The nomenclature used for these products is:

- Light files:

SWOT_L3_LR_WIND_WAVE_<CCC>_<PPP>_<DateBegin>_<DateEnd>_v<Version>.nc

- Extended files:

SWOT_L3_LR_EXTENDED_WIND_WAVE_<CCC>_<PPP>_<DateBegin>_<DateEnd>_v<Version>.nc

Where:

CCC is the number of cycle on 3 digits

PPP is the number of pass on 3 digits

DateBegin and DateEnd are the begin and end dates in UTC of the measurements in each file.

First version is ‘2.0’ to be in line with L3_SSH January 2025 release but may be updated in the future.

4 Change notes

This chapter presents the changes introduced by the successive new product versions.

5 Data format

This chapter presents the data storage format used for the products.

5.1 NetCDF format

The products are stored using the NetCDF format.

NetCDF (network Common Data Form) is an interface for array-oriented data access and a library that provides an implementation of the interface. The netCDF library also defines a machine-independent format for representing scientific data. Together, the interface, library, and format support the creation, access, and sharing of scientific data. The netCDF software was developed at the Unidata Program Center in Boulder, Colorado. The netCDF libraries define a machine-independent format for representing scientific data. Please see Unidata NetCDF pages for more information, and to retreive NetCDF software package on:

https://www.unidata.ucar.edu/software/netcdf/

NetCDF data is:

- Self-Describing. A netCDF file includes information about the data it contains.
- Architecture-independent. A netCDF file is represented in a form that can be accessed by computers with different ways of storing integers, characters, and floating-point numbers.
- Direct access. A small subset of a large dataset may be accessed efficiently, without first reading through all the preceding data.
- Appendable. Data can be appended to a netCDF dataset along one dimension without copying the dataset or redefining its structure. The structure of a netCDF dataset can be changed, though this sometimes causes the dataset to be copied.
- Sharable. One writer and multiple readers may simultaneously access the same netCDF file.

The products are stored in **NetCDF** defined by the Cooperative Ocean/Atmosphere Research Data Service (COARDS) and Climate and Forecast (CF) metadata conventions.

The CF convention generalises and extends the COARDS convention but relaxes the COARDS constraints on dimension and order and specifies methods for reducing the size of datasets. A wide range of software is available to write or read NetCDF/CF files. API are made available by UNIDATA http://www.unidata.ucar.edu/software/netcdf:

- C/C++/Fortran
- Java
- MATLAB, Objective-C, Perl, Python, R, Ruby, Tcl/Tk

5.2 File structure

In addition to these conventions, light and extended products have different NetCDF structures.

Light files share a classic NetCDF structure, whereas extended files use a group and subgroup indexing approach. Each group corresponds to a specific tile size (in km), and certain variables that only depend on the tile dimensions are associated with these groups. Within each tile group, subgroups indexed by geographical box size (in km) contain the remaining variables.

Here is an example of a Light file:

```
netcdf SWOT_L3_LR_WIND_WAVE_006_001_20231102T131911_20231102T141036_v2.0 {
dimensions:
        n_box = 986 ;
        nfy = 21 ;
```

```
        nfx = 20 ;
        nf = 11 ;
        nphi = 72 ;
variables:
        double track_angle(n_box) ;
                track_angle:_FillValue = 214748.3647 ;
                string track_angle:comment = "North relative, 90° = East" ;
                track_angle:coordinates = "longitude latitude" ;
                track_angle:long_name = "Angle between North and satellite flying direction" ;
                track_angle:stndard_name = "heading angle" ;
                track_angle:units = "degrees" ;
        double L18(n_box) ;
                L18:_FillValue = 214748.3647 ;
                L18:comment = "Estimated over the swell partition of Efxfy_SWOT. Corresponds to the equivalent spatial wavelength of dominant partition of waves with periods longer than ~500m (~18s)" ;
                L18:coordinates = "longitude latitude" ;
                L18:long_name = "wavelength taken as the ratio of zeroth and first moment of the spectrum (m0/m1)" ;
                L18:units = "m" ;
        double H18_model(n_box) ;
                H18_model:_FillValue = 214748.3647 ;
                H18_model:comment = "Estimated over the swell partition of Efxfy_model after interpolation into the SWOT fx, fy grid. This spectrum is available in the Extended product" ;
                H18_model:coordinates = "longitude latitude" ;
                H18_model:long_name = "significant wave heigth for waves longer than 18s from WW3 model" ;
                H18_model:units = "m" ;
        int64 swell_mask(n_box, nfy, nfx) ;
                swell_mask:_FillValue = 9223372036854775807LL ;
                swell_mask:comment = "This mask is estimated by isolating the maximum energy pattern over WW3 model spectrum, after interpolation into SWOT cartesian grid and filtering with KaRIn\'s instrument-specific transfer functions. Used to integarte wave parameters from Efxfy_SWOT. 1 = wave energy identified, 0 = no wave energy identified." ;
                swell_mask:coordinates = "longitude latitude" ;
                swell_mask:long_name = "mask for wave energy inside Efxfy_SWOT." ;
                swell_mask:units = "1" ;
        double E_f_phi_SWOT_masked(n_box, nf, nphi) ;
                E_f_phi_SWOT_masked:_FillValue = 214748.3647 ;
                E_f_phi_SWOT_masked:comment = "2D power spectral density of KaRIn L3 250m SSHA, corrected from instrumental transfer functions (OBP averaging, azimuthal PTR and azimuthal cutoff), provided exclusively on the detected swell-masked region in polar nautical coordinates" ;
                E_f_phi_SWOT_masked:coordinates = "longitude latitude" ;
```

E_f_phi_SWOT_masked:long_name = "swell section of Efxfy_SWOT interpolated on polar nautical coordinates" ;

E_f_phi_SWOT_masked:units = "m**2.m**2" ;

double phi_vector(nphi) ;

phi_vector:_FillValue = 214748.3647 ;

phi_vector:long_name = "phase vector for polar E_f_phi_SWOT_masked spectrum" ;

phi_vector:units = "rad" ;

double L18_model(n_box) ;

L18_model:_FillValue = 214748.3647 ;

L18_model:comment = "Estimated over the swell partition of Efxfy_model after interpolation into the SWOT fx, fy grid. This spectrum is available in the Extended product" ;

L18_model:coordinates = "longitude latitude" ;

L18_model:long_name = "wavelength taken as the ratio of zeroth and first moment of the spectrum (m0/m1) from WW3 model" ;

L18_model:units = "m" ;

int64 box_indx(n_box) ;

box_indx:_FillValue = 9223372036854775807LL ;

box_indx:comment = "Index locating the box cross track in the swath, increasing towards the right (satellite frame) 0-1 for 40km boxes, 0-5 for 20km boxes, 0-7 for 10km boxes" ;

double longitude(n_box) ;

longitude:_FillValue = 214748.3647 ;

longitude:comment = "Longitude of measurement. East longitude relative to Greenwich meridian" ;

longitude:long_name = "longitude (degrees East) at box\'s center" ;

longitude:standard_name = "longitude" ;

longitude:units = "degrees_east" ;

double phi18(n_box) ;

phi18:_FillValue = 214748.3647 ;

phi18:comment = "Estimated over the swell partition of Efxfy_SWOT. Corresponds to the equivalent wave direction of dominant partition of waves with periods longer than ~500m (~18s)" ;

phi18:coordinates = "longitude latitude" ;

phi18:long_name = "swell propagation direction taken as the direction of the mean wavenumber vector" ;

string phi18:units = "°" ;

double fx2D(nfy, nfx) ;

fx2D:_FillValue = 214748.3647 ;

fx2D:axis = "X" ;

fx2D:comment = "fx2D is positive to the right of the spacecraft along-track direction" ;

fx2D:long_name = "spatial frequency in cross-track direction" ;

fx2D:units = "cycles per meter (m^-1)" ;

int64 box_indy(n_box) ;

box_indy:_FillValue = 9223372036854775807LL ;

box_indy:comment = "index locating the box along track in the swath, increasing forward (satellite frame)" ;

double H18(n_box) ;

H18:_FillValue = 214748.3647 ;

H18:comment = "Estimated over the swell partition of Efxfy_SWOT. Corresponds to the equivalent significant wave height of dominant partition of waves with periods longer than ~500m (~18s)" ;

H18:coordinates = "longitude latitude" ;

H18:long_name = "significant wave heigth for waves longer than 18s" ;

H18:units = "m" ;

double f_vector(nf) ;

f_vector:_FillValue = 214748.3647 ;

f_vector:long_name = "spatial frequency vector for polar E_f_phi_SWOT_masked spectrum" ;

f_vector:units = "m-1" ;

double latitude(n_box) ;

latitude:_FillValue = 214748.3647 ;

latitude:comment = "Latitude of measurement [-80,80]. Positive latitude is North latitude, negative latitude is South latitude" ;

latitude:long_name = "latitude (positive N, negative S) at box\'s center" ;

latitude:standard_name = "latitude" ;

latitude:units = "degrees_north" ;

double fy2D(nfy, nfx) ;

fy2D:_FillValue = 214748.3647 ;

fy2D:axis = "Y" ;

fy2D:comment = "fy2D is positive towards the spacecraft flying direction" ;

fy2D:long_name = "spatial frequency in along-track direction" ;

fy2D:units = "cycles per meter (m^-1)" ;

double latitude_model(n_box) ;

latitude_model:_FillValue = 214748.3647 ;

latitude_model:comment = "Latitude of WW3 model data [-90,90]. Positive latitude is North latitude, negative latitude is South latitude" ;

latitude_model:coordinates = "longitude latitude" ;

latitude_model:long_name = "latitude (positive N, negative S) of matching WW3 model data" ;

latitude_model:standard_name = "latitude" ;

latitude_model:units = "degrees_north" ;

double index_model(n_box) ;

index_model:_FillValue = 214748.3647 ;

index_model:comment = "Time index of matching WW3 spectrum in monthly WW3 file colocated with KaRIn measurements" ;

index_model:coordinates = "longitude latitude" ;

index_model:long_name = "WW3 model time index" ;

index_model:units = "1" ;

int64 quality_flag(n_box) ;

quality_flag:_FillValue = 9223372036854775807LL ;

quality_flag:comment = "Quality flag for the data presented in this product. Deduced from L3 wind wave processing" ;

quality_flag:coordinates = "longitude latitude" ;

quality_flag:flag_masks = "0LL, 2LL, 4LL, 4096LL, 32768LL" ;

quality_flag:flag_meanings = "good suspect_energy_ratio suspect_number_of_tiles degraded_no_model bad_no_data" ;

quality_flag:long_name = "Quality Flag" ;

quality_flag:standard_name = "valid_flag_for_data" ;

double longitude_model(n_box) ;

longitude_model:_FillValue = 214748.3647 ;

longitude_model:comment = "Longitude of WW3 model data. East longitude relative to Greenwich meridian" ;

longitude_model:coordinates = "longitude latitude" ;

longitude_model:long_name = "longitude (degrees East) of matching WW3 model data" ;

longitude_model:standard_name = "longitude" ;

longitude_model:units = "degrees_east" ;

double time(n_box) ;

time:_FillValue = 214748.3647 ;

time:calendar = "gregorian" ;

time:comment = "Time of measurement in seconds in the UTC time scale since 1 Jan 2000 00:00:00 UTC" ;

time:long_name = "time in UTC at box\'s center" ;

time:standard_name = "time" ;

time:units = "seconds since 2000-01-01 00:00:00.0" ;

double time_model(n_box) ;

time_model:_FillValue = 214748.3647 ;

time_model:calendar = "gregorian" ;

time_model:comment = "Time of WW3 model data in seconds in the UTC time scale since 1 Jan 2000 00:00:00 UTC" ;

time_model:long_name = "time in UTC of matching WW3 data" ;

time_model:standard_name = "time" ;

time_model:units = "seconds since 2000-01-01 00:00:00.0" ;

double phi18_model(n_box) ;

phi18_model:_FillValue = 214748.3647 ;

phi18_model:comment = "Estimated over the swell partition of Efxfy_model after interpolation into the SWOT fx, fy grid. This spectrum is available in the Extended product" ;

phi18_model:coordinates = "longitude latitude" ;

phi18_model:long_name = "swell propagation direction taken as the direction of the mean wavenumber vector from WW3 model" ;

string phi18_model:units = "°" ;

double Efxfy_SWOT(n_box, nfy, nfx) ;

Efxfy_SWOT:_FillValue = 214748.3647 ;

Efxfy_SWOT:comment = "2D power spectral density of KaRIn L3 250m SSHA corrected from instrumental transfer functions (OBP averaging, azimuthal PTR and azimuthal cutoff)" ;

Efxfy_SWOT:coordinates = "longitude latitude" ;

Efxfy_SWOT:long_name = "PSD of KaRIn L3 250m sea surface heigth anomaly corrected from instrumental effects" ;

Efxfy_SWOT:units = "m^2.m^2" ;

// global attributes:

:Conventions = "CF-1.7" ;

:Metadata_Conventions = "Unidata Dataset Discovery v1.0" ;

:cdm_data_type = "Swath" ;

:comment = "Wind/wave measured by KaRIn" ;

:contact = "aviso@altimetry.fr" ;

:creator_email = "aviso@altimetry.fr" ;

:creator_name = "DUACS - Data Unification and Altimeter Combination System" ;

:creator_url = "https://aviso.altimetry.fr" ;

:data_used = "SWOT KaRIn SWOT_L3_LR_SSH_Unsmoothed (CLS/CNES). DOI associated: https://doi.org/10.24400/527896/A01-2024.003" ;

:doi = "https://doi.org/10.24400/527896/A01-2024.016" ;

:institution = "LOPS, CLS, CNES" ;

:license = "https://www.aviso.altimetry.fr/fileadmin/documents/data/License_Aviso.pdf" ;

:platform = "SWOT" ;

:processing_level = "L3" ;

:project = "VAGUES, DESMOS, DUACS" ;

:references = "https://aviso.altimetry.fr" ;

:source = "Altimetry measurements" ;

:title = "SWOT KaRIn Global Ocean swath Wind Wave L3 product" ;

:product_version = "2.0" ;

:geospatial_lat_min = -77.984774 ;

:geospatial_lat_max = 77.976203 ;

:geospatial_lat_units = "degrees_north" ;

```
                :geospatial_lon_min = 0.044569 ;
                :geospatial_lon_max = 359.99371 ;
                :geospatial_lon_units = "degrees_east" ;
                :history = "2024-12-24T16:23:46Z: Created by WIND WAVE KaRIn prototype" ;
                :date_created = "2024-12-24T16:23:46Z" ;
                :date_issued = "2024-12-24T16:23:46Z" ;
                :date_modified = "2024-12-24T16:23:46Z" ;
                :time_coverage_start = "2023-11-02T13:19:11Z" ;
                :time_coverage_end = "2023-11-02T14:10:36Z" ;
}
```

And below is an example of the architecture of an Extended file without displaying variables and global attributes (replaced by "…").

```
netcdf SWOT_L3_LR_WIND_WAVE_Extended_006_485_20231102T131911_20231102T141036_v2.0 {

// global attributes:
                …

group: tile_5km {
  dimensions:
          nfy = 21 ;
          nfx = 20 ;
          nf = 11 ;
          nphi = 72 ;
  variables:
          ...

  group: box_40km {
    dimensions:
          n_box = 986 ;
          nind = 4 ;
    variables:
          ...
    } // group box_40km

  group: box_10km {
    dimensions:
          n_box = 27636 ;
          nind = 4 ;
    variables:
          ...
    } // group box_10km
  } // group tile_5km

group: tile_10km {
  dimensions:
          nfy = 42 ;
          nfx = 40 ;
          nf = 20 ;
          nphi = 144 ;
  variables:
          ...

  group: box_20km {
```

```
    dimensions:
            n_box = 5922 ;
            nind = 4 ;
    variables:
            ...
    } // group box_20km

  group: box_40km {
    dimensions:
            n_box = 986 ;
            nind = 4 ;
    variables:
            ...
    } // group box_40km
  } // group tile_10km
}
```

6 Known features

6.1 Effect of gapfilling

SSHA values whose quality flag is different from specific values (section 2.1) are neglected. In the spectral estimation process, SSHA gaps are filled with the median value of the respective tile. In some cases, this might induce extra energy at high frequencies close to the limits of the spectrum.

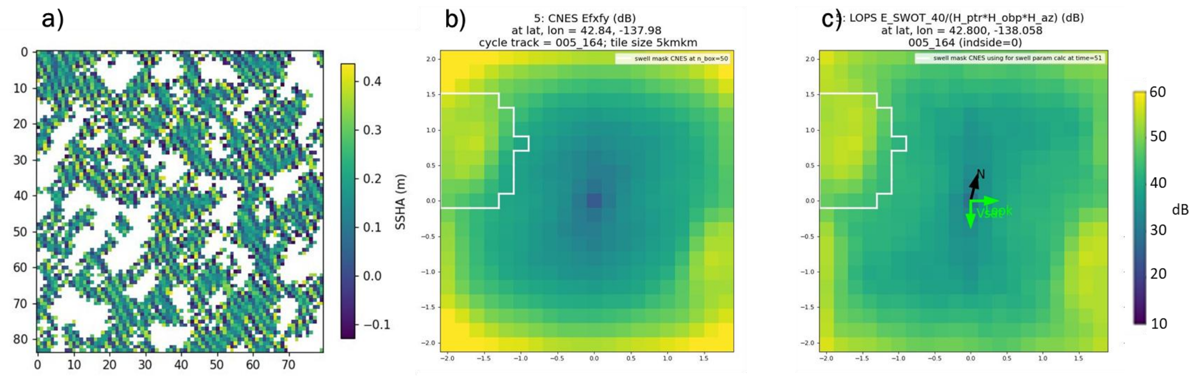

Figure 6 - a) Snapshot of SSHA with masked pixels (in white) according to the quality flag values described in section 2.1. b) L3 WW spectrum over this region. C) Spectrum of heights if no masking was applied to the SSHA matrix

To prevent this type of artifacts, tiles with more than 25% of SSHA gaps are rejected. Moreover, the L3 WW flag value 4 is raised when the number of tiles used for fft computation is less than 25% of the expected number of tiles.

Future versions of the product will probably improve the flagging and gap management of the input SSHA fields.

6.2 Effect of multiple mask clusters

Sometimes, the values of L18 and phi18 variables show spatial discontinuities that are due to the change from one detected swell cluster to multiple detected swell clusters (Figure 7). The wave parameters are computed over the spectrum pixels identified as swells, no matter if they belong to different separate swell clusters or not. For this reason, the L18 and phi18 approximately represent the mean wavelength and direction over the detected swell clusters.

Future versions of the product will probably include more advanced partitioning algorithms that should allow to provide wave parameters for each swell cluster.

6.3 Residual signatures of instrumental corrections

As introduced at the end of section 2.3, the KaRIn SSHA power spectral density is divided by an approximation of the KaRIn transfer function that includes the azimuth PTR, the on-board averaging filters and the azimuth cutoff effect. This correction is done on the assumption that the KaRIn processing is linear, so the radar and interferometric processing steps would act on the estimated heights as they act on the interferometric phase. Moreover, the validity of the azimuth cutoff correction due to surface movement has yet to be assessed. Other elements have not been considered, such as the correlation between KaRIn beams and their combination in the ground segment, or the non-linear effects on heights due to waves and speckle. For these reasons, we expect the L3 WW spectra to contain residual errors from the instrumental corrections applied, although we cannot predict them with precision in advance.

In some regions, the L3 WW spectra show an excess of energy towards high along-track frequencies (Figure 8). After analysis of the region, model and in-situ data and the processing chain, we conclude that this extra energy is probably a signature of the instrumental correction errors mentioned above.

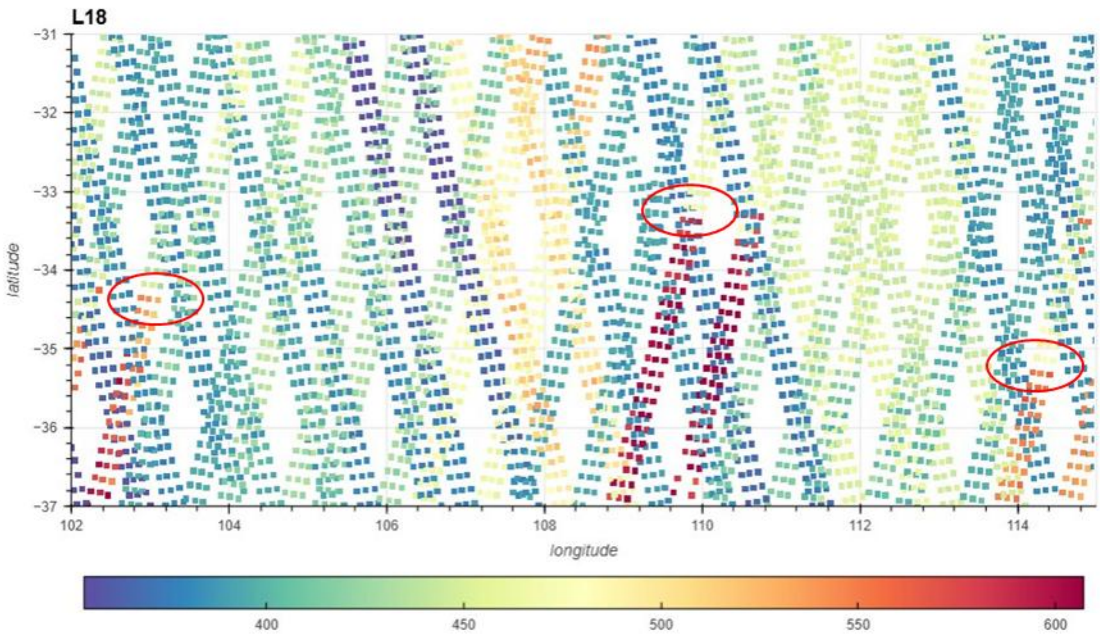

Figure 7 - A map of L18 values depicting spatial discontinuities that are coincident with a change in swell clustering, from one detected cluster to two detected clusters

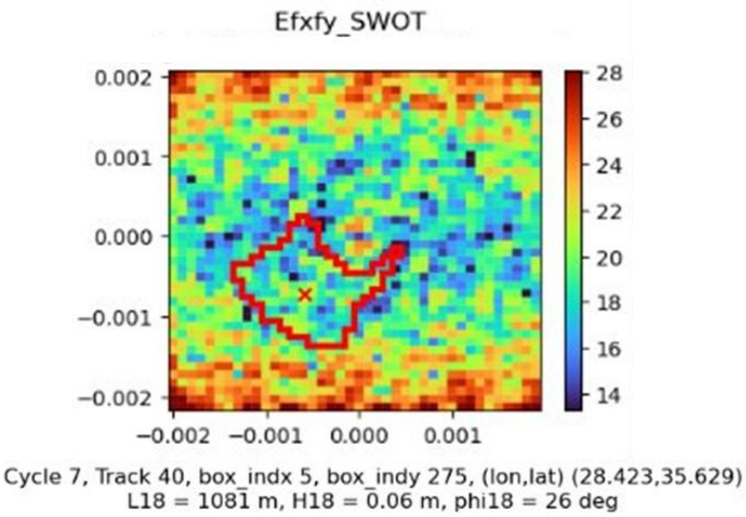

Figure 8 – display of one occurrence of the variable Efxfy_SWOT where the excess of energy at high along-track frequencies is clearly visible

7 Accessibility of the products

If you already have an AVISO account, data access is available through the following services:

CNES AVISO FTP/SFTP (with AVISO+ credentials)

- FTP access: ftp://ftp-access.aviso.altimetry.fr:21
- SFTP access: sftp://ftp-access.aviso.altimetry.fr:2122
    - /swot_products/l3_karin/l3_lr_wind_wave

CNES AVISO THREDDS Data Server, TDS (with AVISO+ credentials)

- TDS access:
https://tds-odatis.aviso.altimetry.fr/thredds/catalog/L3/dataset-l3-swot-karin-wind-wave.html

8 Contact

For more information, please contact:

Aviso+ User Services
E-mail: aviso@altimetry.fr
On Internet: https://www.aviso.altimetry.fr/

The user service is also interested in user feedbacks; questions, comments, proposals, requests are much welcome.

9 Bibliography

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