Along-track Nadir Level-2+ (L2P) Significant Wave Height (SWH) from SWIM instrument of CFOSAT Product Handbook

Nomenclature: SALP-MU-P1-OP-23414-CLS

Issue: 1 rev 0

Date: April 2020

Chronology Issues:			
Issue:	Date:	Validated by	Reason for change:
1.0	2020/04/08		Creation of the document

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List of Acronyms:

AVISO+	Archiving, Validation and Interpretation of Satellite Oceanographic data
CaSyS	CalVal Systematic SWIM
CLS	Collecte, Localisation, Satellites
Cnes	Centre National d'Etudes Spatiales
ECMWF	European Centre for Medium-range Weather Forecasting
FROGS	Frogs Oceanographic Ground Segment
IGDR	Interim Geophysical Data Record(s)
L2P	Level-2+ product: global 1 Hz along-track data (sea level anomaly, its components and validity flag) over marine surfaces based on Level-2 products
Nasa	National Aeronautics and Space Administration
NRT	Near Real Time
NTC	Non Time Critical
OSDR	Operational Sensor Data Records
POE	Precise Orbit Ephemeris
RD	Reference Document
SAR	Synthetic Aperture Radar
Ssalto	Segment Sol multimissions d'ALTimétrie, d'Orbitographie et de localisation précise.
SLA	Sea Level Anomaly
SSB	Sea State Bias
SSH	Sea Surface Height
SWIM	Surface Waves Investigation and Monitoring
TAI	IAT - International Atomic Time
UTC	Universal Time Coordinated

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Bibliography

[1] Sepulveda H. H., Queffeulou P. and Ardhuin F. (2015): Assessment of SARAL AltiKa wave height measurements relative to buoy, Jason-2 and Cryosat-2 data. Marine Geodesy, 38 (S1),449-465, doi: 10.1080/01490419.2014.1000470.

[2] N. Taburet, R. Husson, E. Charles, Quality Information Document WAVE Thematic Assembly Centre: WAVE_GLO_WAV_L3_SWH_NRT_OBSERVATIONS_014_00

[3] Queffeulou P. (2016): Validation of Jason-3 altimeter wave height measurements (poster). OSTST meeting, November 1-4, 2016, La Rochelle, France.

[4] Queffeulou P. and Croizé-Fillon D. (2017): Global Altimeter SWH Data Set, version 11.4, February 2017. Technical report Ifremer. ftp://ftp.ifremer.fr/ifremer/cersat/products/swath/altimeters/waves/documentation/altimeter_wave_merge__11.4.pdf

[5] Hauser D., Tourain C., Hermozo L. et al (2020): New Observations from the SWIM radar on board CFOSAT: instrument validation and ocean wave measurement assessment, IEEE [Submission in progress]

Contents

1. Introduction

The purpose of this document is to describe the Along-track Nadir Level-2+ (L2P) Significant Wave Height (SWH) from SWIM instrument of CFOSAT.

The generation of those products is part of the FRench Oceanographic Ground Segment (FROGS) of the CFOSAT Mission. The dissemination of those products is part of the Cnes Aviso+.

After a description of the input data, a short overview of the processing steps is presented. Then complete information about user products is provided, giving nomenclature, format description, and software routines.

2. Overview

2.1. SWIM SWH nadir measurements

SWIM (Surface Waves Investigation and Monitoring instrument) is one of CFOSAT's radar instruments. It is a wave scatterometer operated at near-nadir incidences: 0° (nadir), 2°, 4°, 6°, 10°. At 0° incidence SWIM behaves as a conventional altimeter, it sends a spherical radar signal in nadir direction.

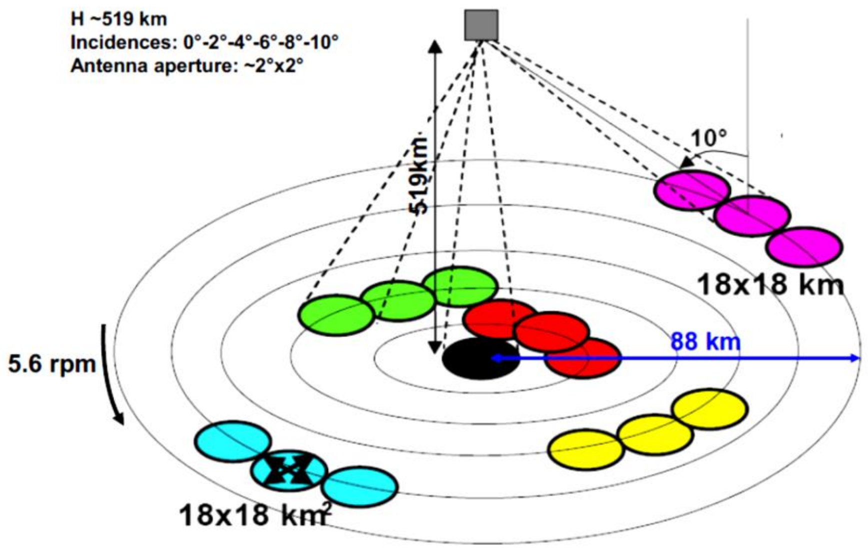

Figure 1. SWIM scatterometer

This signal is reflected by the sea surface and goes back to the satellite. The analysis of the returned signal allows the calculation of the time needed by the signal to go and come back from which can be deduced the distance satellite-sea surface. The sea state surface elevation distribution impacts the shape of the returned signal, the so-called "waveform".

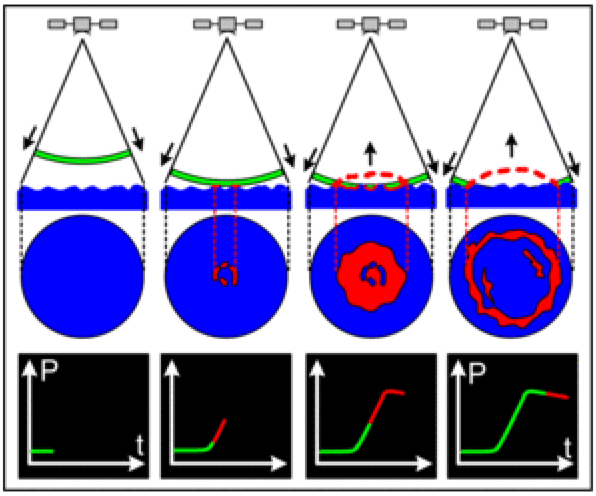

Figure 2. Formation of an echo over a sea surface with waves for conventional altimetry

While the signal is not reflected at the ocean surface, the altimeter only receives passive information from the natural radiations of the atmosphere, the "thermal noise", that creates a low energy plateau. Then the signal propagates at the surface of the ocean, and, as the number of scatterers increases, the backscattered power increases as well. The pulse duration being limited, and because the antenna gain decreases when going far from nadir, the returned power of the echo decreases slowly. The resulting wave is called the "waveform" (Figure 2).

Hence, the Significant Wave Height (SWH) over ocean surfaces is determined from the slope between the leading edge and the highest point of the radar altimeter waveform. For high waves, it will take longer for the signal to propagate and return, resulting in a wider waveform. For very reflective surfaces and small waves, the waveform will be steeper, and the distance between the leading edge and the highest point will be smaller.

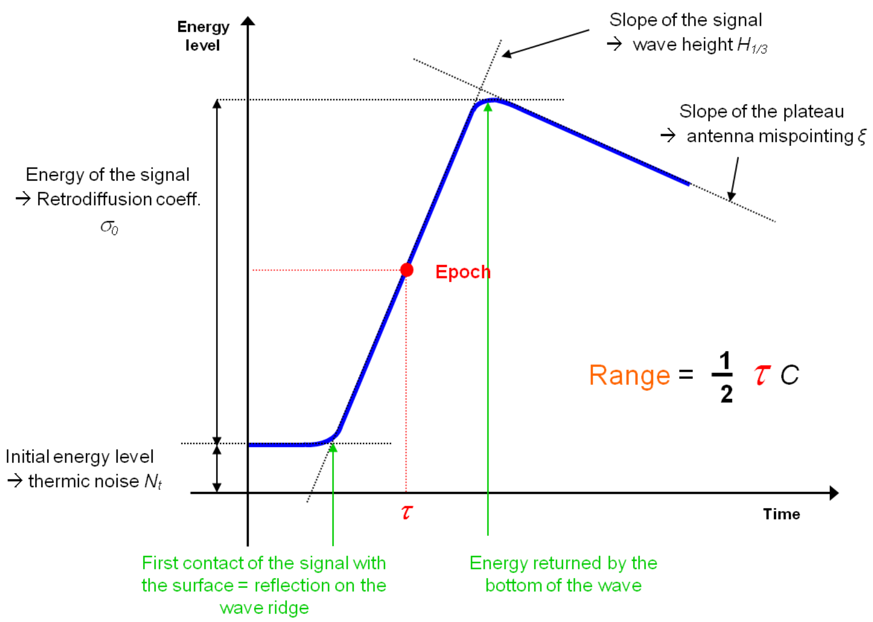

Figure 3. Nadir Waveform

The term Significant Wave Height (SWH or Hs) refers to the mean wave height of the highest third of the waves (also sometimes denoted $H_{1/3}$).

2.2. Orbits, Passes and Repeat cycle

'Orbit' is one revolution around the Earth by the satellite.

'Repeat Cycle' is the time period that elapses until the satellite flies over the same location again.

For CFOSAT:

- The orbit is sun-synchronous with an ascending pass at the equator around 7am;
- The inclinaison is 97.465 deg ;
- The passes are numbered from 1 to 197 representing a full 'repeat cycle' for the repetitive orbit;
- The repeat cycle is 13 days.

Every "orbit" of a given cycle flies over the same path as the orbit of all other cycles in the same repeat-cycle phase and covers oceans basins continuously.

The localisation of orbits (for realised and extrapolated cycles) can be found on the AVISO+ web site:

https://www.aviso.altimetry.fr/en/data/tools/pass-locator.html

3. L2P files production

3.1. Overview

SWIM L2P product intends to be a calibrated, easy-to-ingest product with comparable metrics. This is in order to provide user friendly CFOSAT nadir products where users can directly access to valid significant wave height content without additional processing. Nadir products will contain:

- only valid measurements of SWIM;
- a sub-ensemble of variables extracted from SWIM NRT files generated by the CWWIC;
- Calibrated and unbiased data in compliance with the nadir constellation reference frame.

The processing can be divided in 4 main parts:

- Pre-processing;
- Calibration;
- Data editing;
- Products generation.

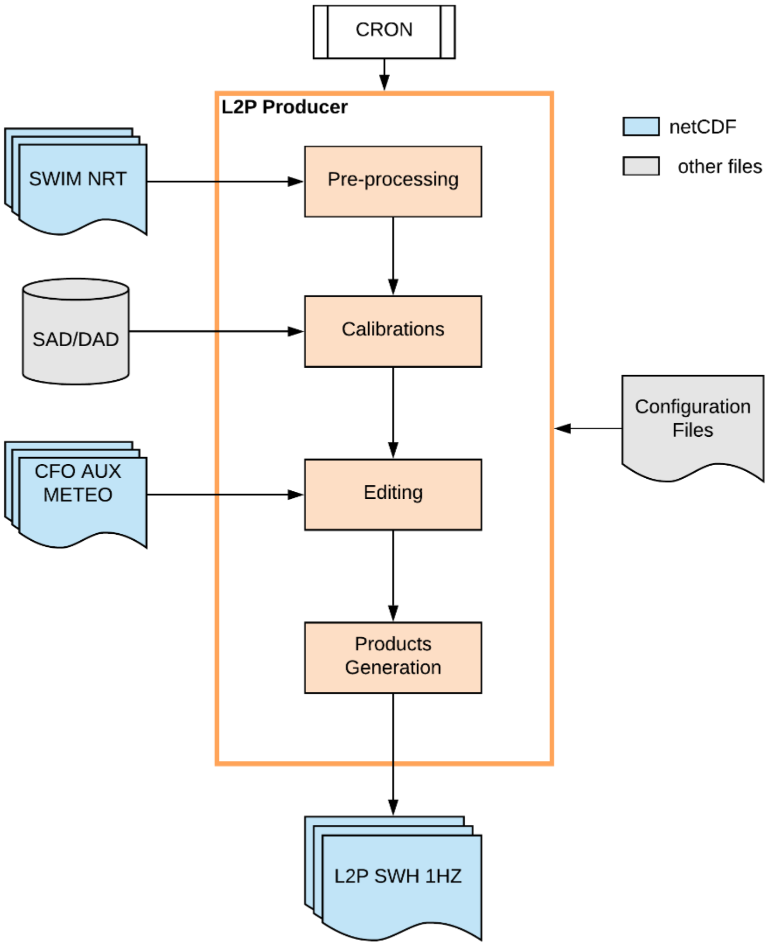

Figure 4. Processing L2P SWH CFOSAT

3.2. Pre-processing

The measurements used in the system consist in Near-Real-Time (NRT) CFOSAT Level-2 products. The Jason-3 mission is also considered in a cross calibration performed between Jason-3 and CFOSAT. The cross calibration data (abacus) has been defined from crossover points between CFOSAT and Jason-3.

Pre-processing consists in:

- making a prior selection to process only new files;
- handling compliancy with C.F. 1-6;
- adapt and copy variables that do not need calibration or editing (e.g: latitude, longitude, …).

Dimensions are set to be compliant with CF 1.6.

3.3. Data Calibration

Calibration is divided in two main steps (see Figure 5): cross-calibration on the reference mission and absolute calibration on in-situ data. The first step consists in homogenizing SWH data by calibrating CFOSAT on the reference mission (Jason-3). The second step consists in applying a correction computed between the reference mission and in-situ measurements provided by buoys.

The next sub-sections describe the computation of the two main calibrations: cross-calibration and absolute calibration.

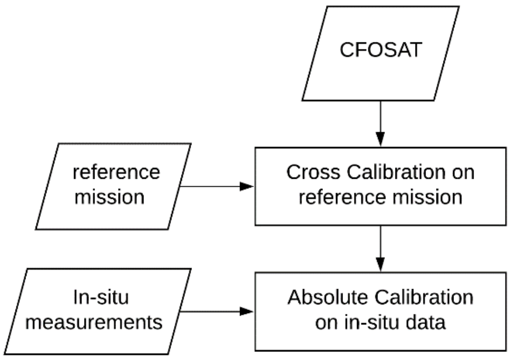

Figure 5. Description of the calibration process

3.3.1.1. Cross-calibration

Cross-calibration consists in determining the relation between the significant wave height measurements provided by two different missions. This relation is determined on a representative number of collocated measurements and then used in the operational system to homogenise the missions with respect to the reference one. Such a relation is expected to remain valid as long as instrumental drifts are not detected or ground segment evolutions do not affect the L2 products in input of the operational system. Should one of these evolve, another cross-calibration relation should be computed and implemented into the operational system.

Jason-3 is used as the reference mission as it is a conventional altimeter mission, expected to show robust results for SWH measurements.

Crossover points between the two mission orbits are determined. For SWH measurements calibration, only crossover points with a time difference less than 3 hours are considered. This short delay ensures that both missions observe a scene that did not significantly evolve (when a longer dataset archive is available, this time difference can be lowered to 1 hour). The along-track SWH of CFOSAT and Jason-3 are interpolated at the selected crossover points. The interpolation technique uses a linear approximation in the along-track direction, based on the 1Hz data samples of each mission (SWIM and Jason-3).

Once the two mission measurements are collocated, the differences between the reference mission and the secondary mission significant wave heights are computed. The bias is plotted as a function of the secondary mission wave height in order to provide a height-dependent bias correction. The next step consists in fitting a polynomial function to the distribution of this bias. This function is stored in an abacus file used as an input in the L2P wave processing chain.

Details on the calibration relations are provided in Appendix 9.1.

3.3.1.2. Absolute calibration

Once inter-mission biases are removed, using the cross-calibration corrections described in the previous section, an absolute calibration correction is applied. This absolute calibration aims at correcting the biases between in-situ measurements and satellite altimetry. CFOSAT mission is cross-calibrated on the reference mission Jason-3. Therefore, the absolute calibration is computed from the comparison of Jason-3 significant wave heights to buoy measurements at collocated points.

Details on the calibration relations are provided in Appendix 9.2.

3.4. Data Editing

Quality Control on the input L2 data is a critical process; it is aimed at providing only the most reliable data. The system uses as input the L2 products which contain all the variables derived from the SWIM nadir beam observations (e.g: sigma0, compressed variables from 5Hz to 1Hz) as well as flags and calibrated 1Hz-nadir swh obtained from the previous step (cf. 3.3 Data Calibration). These values are provided at 1-Hz frequency except for the sea-ice coverage which is at 5Hz frequency.

Parameter	Units	Method	SWIM Valid Value or Min/Max
Nadir SWH 1HZ	m	Threshold	0 < x < 30
Nadir SWH 1HZ std	m	Abacus	X < Abacus Value
Number of SWH-5Hz measures used to compute SWH-1Hz	1	Threshold	4 ≤ x ≤ 5
Nadir wind 1Hz	m/s	Threshold	0 < x < 30
Nadir sigma0 1HZ	dB	Threshold	5 < x < 25
Nadir sigma0 1HZ std	dB	Threshold	0 < x < 2
Nadir sigma0 1HZ used native	1	Threshold	4 ≤ x ≤ 5

Flag valid SWH 1hz	1	Flag value	x = 0
Ice cover from ECMWF	pct	Flag value	x = 0.0

Table 1. Flag and threshold editing criteria

Data are selected as valid or invalid using a combination of various criteria such as quality flags and parameter thresholds (see Table 1 for details). These criteria are adapted from the ones used for the Sea Level Anomaly in altimeter missions (e.g. Aviso/SALP 2016). Only criteria related to retracking derived values were selected. Geophysical parameters (e.g. tropospheric corrections) do not intervene in the SWH estimation and therefore are not used in the wave products generation. Consequently, no editing criterion was set for these parameters in the L2P wave chain. For CFOSAT, the criteria on the off-nadir angle are not activated since their values are not derived from the retracking, therefore their value do not provide information about SWH data quality. As CFOSAT is not an altimeter mission, there is no precise orbit determination; thus the orbit and the range are not considered in the editing.

The method to compute the threshold on SWH RMS is described in Queffelou P. (2016) [3]. This method has been tuned for CFOSAT 1Hz data. It consists in determining a threshold on the 1Hz SWH standard dispersion. Such a threshold is defined as the sum of the mean value and three times the standard deviation of the gaussian fit applied to ln(SWH_STD) (e-base logarithm) distribution for each SWH bin (Figure 6). The curve representing the thresholds as a function of SWH is then filtered (red line in Figure 7: Left). Values for which 5m<SWH<9m are used to determine a linear fit used for SWH>5m. Finally the threshold on ln(SWD_STD) is converted back into a threshold on SWH_STD (Figure 7: Right). This threshold depends on SWH and potentially on the processing baseline. It is recomputed when processing baseline evolutions impact the SWH estimation.

For example, on cycle 21 from July 19th to August, 1st 2019, this threshold edits 13,94% of data (continental data are not considered).

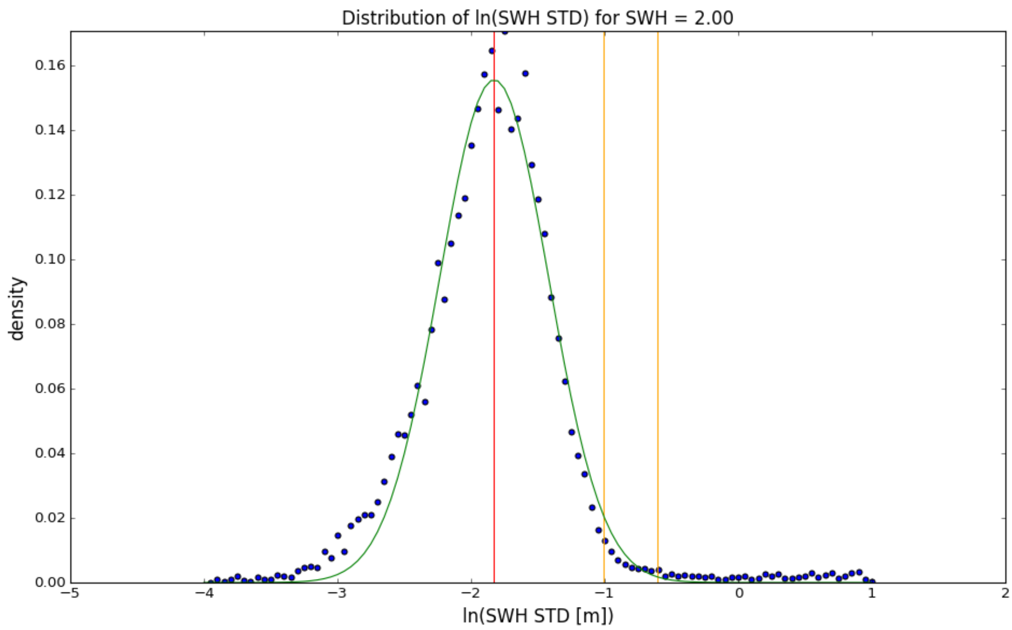

Figure 6. Distribution of ln(SWH_STD) for SWH between 2m and 2.1m CFOSAT 13 days from 2019 July 19th to 2019 August 1st. The green line represents the gaussian fit on the distribution. The red line is the mean from the gaussian fit, the orange lines represent mean +2sigma and mean+3sigma where sigma is the standard deviation

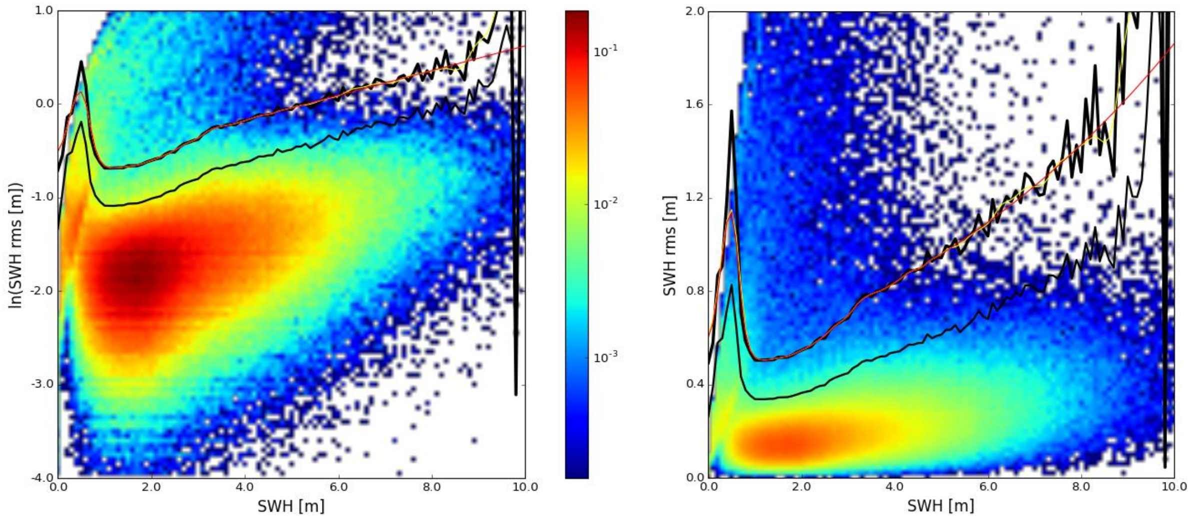

Figure 7. Density plots of ln(SWH RMS) and SWH RMS as a function of SWH, and their computed thresholds. CFOSAT 13 days from 2019 July 19th to 2019 August 1st. The black lines represent mean+2sigma and mean+3sigma. Left: The red line represents the smoothed mean+3sigma curve for SWH<5m and for SWH ≥5m consist in an affine function. Density colour scales logarithmically. Right: The red line is the limits applied on std(swh)

4. Product Presentation

4.1. Temporal Availability

CFOSAT Nadir L2P are available from the 29th of July 2019 (8h41), corresponding to the 4.3.2 baseline evolution for the CWWIC chain (L2 production). Production has no ending date as it is still on going.

4.2. Nomenclature

CFOSAT L2P filenames are named under CFOSAT L2 model:

CFO_OPER_SWI_L2P____F_<begin_date>T<begin_hour>_<end_date>T<end_hour>.nc

Where the name components are:

- <begin_date> under Year-Month-Day format : YYYYMMDD;
- <end_date> under Year-Month-Day format : YYYYMMDD;
- <begin_hour> under Hour-Minute-Second format : HHmmss;
- <end_hour> under Hour-Minute-Second format : HHmmss.

This is a filename example:

CFO_OPER_SWI_L2P____F_20200306T180424_20200306T194835.nc

5. Data Format

This chapter presents the data storage format and convention used for CFOSAT L2P Wave products. All products are distributed in NetCDF-4 with norm CF. NetCDF (Network Common Data Form) is an open source, generic and multi-platform format developed by Unidata. An exhaustive presentation of NetCDF and additional conventions is available on the following web site:

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

All basic NetCDF conventions are applied to files. Additionally, the files are based on the attribute data tags defined by the Cooperative Ocean/Atmopshere Reasearch Data Service (COARDS) and Climate 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 made available by UNIDATA:

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

5.1. L2P Wave Product Format

5.1.1. Dimensions

One dimension is defined:

- time: number of data in current file, sampled at 1Hz.

5.1.2. Data Handling Variables

Variables defined in the product have the following definitions:

Name of variable	Type	Content	Unit	Timeliness
latitude	int	Latitude value of measurements	degrees_north	all
longitude	int	Longitude value of measurements	degrees_east	all
time	double	Time of measurements	seconds since 2000-01-01 00:00:00 UTC	all
validation_flag	byte	Validity of Significant wave Height valid=(validation_flag=0), invalid=(validation_flag=1)	none	all
swh	short	Significant wave height	meters	all
applied_bias	short		meters	all

Table 2. Description of L2P netCDF variables

The mapping between variables of L2 products and variables of L2P products is available in Table 3.

5.1.2.1. Attributes

Additional attributes may be available in L2P wave files. They are providing information about the type of product or the processing and parameter used.

5.1.2.2. Example of L2P Nadir Wave File

```
netcdf CFO_OPER_SWI_L2P____F_20200306T180424_20200306T194835 {
dimensions:
	time = 6244 ;
variables:
	int latitude(time) ;
		latitude:long_name = "latitude" ;
		latitude:standard_name = "latitude" ;
		latitude:scale_factor = 1.e-06 ;
		latitude:units = "degrees_north" ;
		latitude:valid_max = 90000000LL ;
		latitude:valid_min = -90000000LL ;
		latitude:comments = "Positive latitude is North latitude, negative latitude is South latitude." ;
	int longitude(time) ;
		longitude:long_name = "longitude" ;
		longitude:standard_name = "longitude" ;
		longitude:scale_factor = 1.e-06 ;
		longitude:units = "degrees_east" ;
		longitude:valid_max = 360000000LL ;
		longitude:valid_min = 0LL ;
		longitude:comments = "East longitude relative to Greenwich meridian" ;
	double time(time) ;
		time:units = "seconds since 2000-01-01 00:00:00.0" ;
		time:long_name = "time (sec. since 2000-01-01)" ;
		time:standard_name = "time" ;
		time:calendar = "gregorian" ;
		time:axis = "T" ;
	byte validation_flag(time) ;
		validation_flag:_FillValue = -127b ;
		validation_flag:flag_meanings = "valid_data_over_ocean rejected_data" ;
		validation_flag:flag_values = 0b, 1b ;
		validation_flag:coordinates = "longitude latitude" ;
		validation_flag:long_name = "validation flag" ;
	short swh(time) ;
		swh:_FillValue = -32767s ;
		swh:quality_flag = "validation_flag" ;
```

```
        swh:scale_factor = 0.001 ;
        swh:standard_name = "sea_surface_wave_significant_height" ;
        swh:comment = "Bias corrected. Calibration relative to buoys [Sepulveda et al, 2015]. Initial L2 swh values can be recomputed using swh + applied_bias." ;
        swh:long_name = "Significant Wave Height on main altimeter frequency band" ;
        swh:valid_min = 0LL ;
        swh:coordinates = "longitude latitude" ;
        swh:units = "m" ;
        swh:valid_max = 32767LL ;
    short applied_bias(time) ;
        applied_bias:_FillValue = -32767s ;
        applied_bias:comment = "bias correction for calibration. The bias correction depends on the swh value. This bias is already taken into account in the swh variable." ;
        applied_bias:scale_factor = 0.001 ;
        applied_bias:coordinates = "longitude latitude" ;
        applied_bias:long_name = "Significant Wave Height bias correction" ;
        applied_bias:valid_min = -30000LL ;
        applied_bias:units = "m" ;
        applied_bias:valid_max = 30000LL ;

// global attributes:
        :platform = "CFOSAT" ;
        :sensor = "SWIM" ;
        :institution = "CNES" ;
        :contact = "" ;
        :comment = "Significant Wave Height measured by altimetry" ;
        :last_meas_time = "2020-03-06 19:48:34" ;
        :software_version = "production_l2p: 2.3.0" ;
        :product_version = "1.0" ;
        :Conventions = "CF-1.6" ;
        :first_meas_time = "2020-03-06 18:04:24" ;
        :creation_date = "2020-03-06T20:30:12" ;
        :processing_level = "L2P" ;
}
```

5.2. Mapping between L2 and L2P variables

Hereafter the mapping between variables of SWIM NRT and SWIM L2P products is listed (in the case that L2P products contain the same content as L2 products).

Name of L2P variable	Name of L2 NRT variable	Content
latitude	lat_nadir_1Hz	Latitude value of measurements
longitude	lon_nadir_1Hz	Longitude value of measurements
time	time_nadir_1Hz	Time of measurements
validation_flag		Validity of Significant wave height valid=(validation_flag=0), invalid=(validation_flag=1)
swh		Note that in L2P the provided swh value is based on L2 variable 'nadir_swh_1Hz' but calibrated on Jason-3 and buoys.
applied_bias		Adding this value to swh allows recovering the original L2 swh value

Table 3. Mapping between variables in SWIM NRT and L2P files

6. Products policy and accessibility

The use of the CFOSAT L2P products is described in the AVISO+ License Agreement.

CFOSAT L2P products are available via authenticated servers:

- On authenticated AVISO+ FTP (online products):
    - You need to register via AVISO+ web portal and sign the License Agreement: http://www.aviso.altimetry.fr/en/data/data-access/registration-form.html and select the product "Wave / wind CFOSAT products".

  Information to access the data will be sent by email.

    - Once you are registered, the access to the products is given in your personal MY AVISO+ account in the 'product page' available on: https://www.aviso.altimetry.fr/no_cache/en/my-aviso-plus.html

- On the authenticated AVISO+ CNES Data Center (archived products):
  Register and download on https://aviso-data-center.cnes.fr/

7. News, updates and reprocessing

7.1. Operational news

To be kept informed about events occurring on the satellites and on the potential services interruption, see the operational news on the Aviso+ website:

https://www.aviso.altimetry.fr/no_cache/en/news/operational-news-and-status.html

7.2. Updates and reprocessing

Information about updates and reprocessing are described in

https://www.aviso.altimetry.fr/data/product-information/updates-and-reprocessing/monomission-data-updates.html

7.3. Additional Data and Citation

Information about the starting dates of each cycle can be found at the following webpage under Localisation of Measurements :

https://www.aviso.altimetry.fr/en/missions/current-missions/cfosat.html

RECOMMENDATIONS TO CFOSAT USERS ON PUBLICATION POLICY:

The first scientific publications on CFOSAT data will be authored by members who participated to the verification and CAL/VAL phase since the satellite launch. Two papers, one on SWIM and one on SCAT are currently under review for publication in IEEE Trans. on Geoscience and Remote Sensing (February 2020).

It is recommended that all further publications based on CFOSAT data cite one of these first two publications (depending on whether they deal with SCAT or SWIM). The publications co-authored by several members and groups of the Joint Science Team is firmly encouraged.

All the publications and communications based on CFOSAT data have to be forwarded to CNSA and CNES (send to aviso@altimetry.fr who will transmit) and they all have to acknowledge CNSA and CNES as having ownership of the CFOSAT science products. The acknowledgement sentence is: “All CFOSAT data are provided by courtesy of CNSA and CNES [under science proposals XXX. (XXX=proposal id)]."

8. Contacts

For more information, please contact:

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11 rue Hermès
Parc Technologique du canal
F-31520 Ramonville Cedex
France
E-mail: aviso@altimetry.fr
On Internet: https://www.aviso.altimetry.fr/

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

9. Appendix

9.1. Cross-Calibration

CFOSAT crossover points with Jason-3 were computed on a 117-day period (November 1st, 2018 to February 26th, 2019). The starting date corresponds to the beginning of the production of CFOSAT product with AWWAIS 4.2 (CWWIC Product Version).

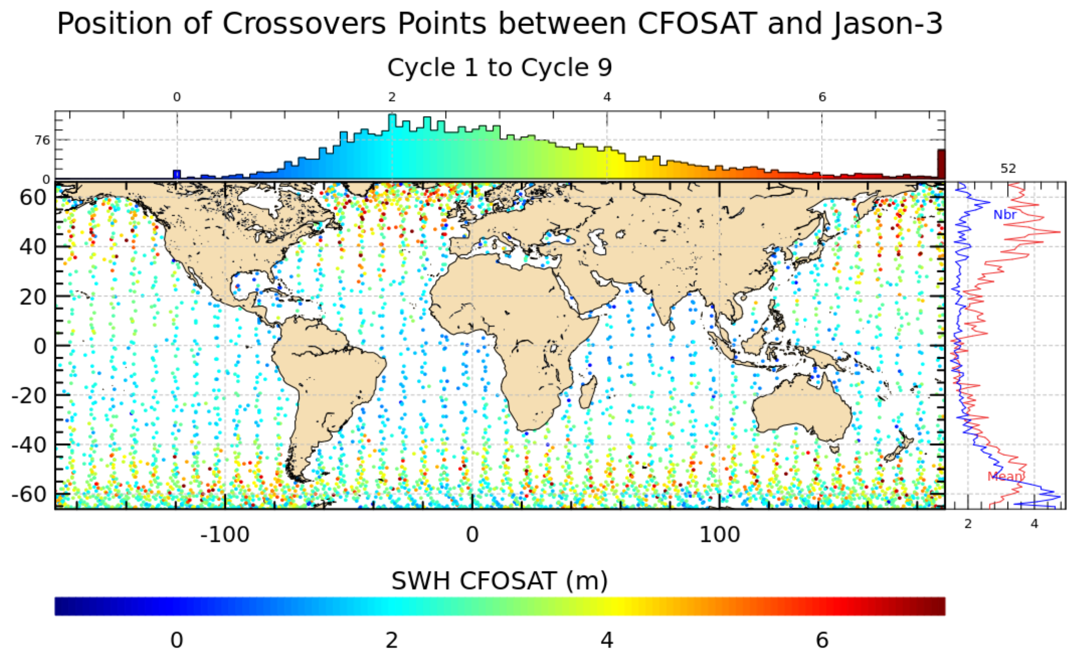

Figure 8. Spatial Distribution of Jason-3 and CFOSAT Crossover points

Crossover method was performed with a time constraint of a 3-hours difference between the two satellites. The blue dots in Figure 9 (top) represent the median of the difference between CFOSAT and Jason-3 SWH values inside each 10-cm bin of the CFOSAT population.

A linear fit is performed to determine the bias as a function of the significant wave height. The selected fitting function is the one computed over the [1-6 m] range (orange) as it samples most of the population.

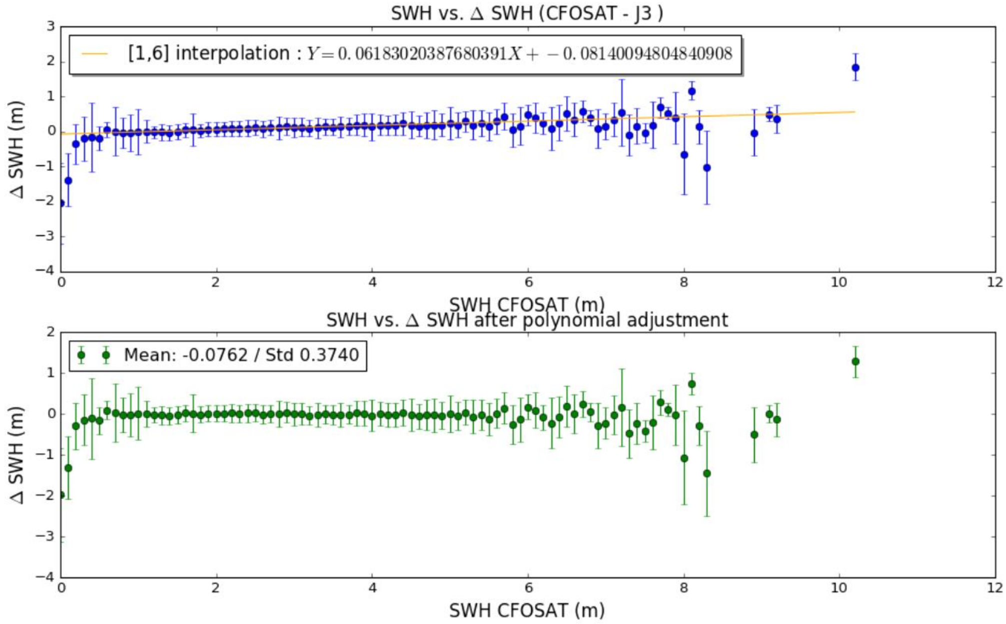

Figure 9. Top: Median of the difference between CFOSAT and J3 SWH values at crossovers points per 10cm bin. Error bars represent the standard deviation of the difference inside each bin. The orange curve represents the linear fit over the [1-6] meters range. Bottom: Residuals between the median and the fit.

The linear correction retrieved for cross-calibration between CFOSAT and Jason-3 is:

$$Corr(CFO/J3) = 0.0618H - 0.081$$

Equation 1: Linear correction between CFOSAT and Jason-3 SWH

9.2. Absolute Calibration

Once inter-mission biases are removed, using the cross-calibration corrections described in the previous section, an absolute calibration correction is applied to all missions. This absolute calibration aims at correcting the biases between in-situ measurements and satellite altimetry. All the missions are cross-calibrated on the reference mission Jason-3. Therefore, the absolute calibration is computed from the comparison of Jason-3 significant wave heights to buoy measurements at collocated points.

According to results from Queffeulou [3], performances for Jason-3 are very similar to those given by Jason-2 and can thus be applied to compensate for systematic errors. The linear correction is given below (Queffeulou and Croizé-Fillon 2017 [4]):

$$Corr(J2/buoys) = -1.0149H + 0.0277$$

Equation 2: Linear correction for absolute calibration of Jason-2 SWH with respect to buoy measurements

Comparisons between Jason-3 and Jason-2 along-track 1 Hz collocated measurements during Jason-3 commissioning (same track, 80 s difference between the two altimeters), were performed to compare sea state sensed by the two altimeters at the same geographical location (Figure 10). The left plot shows 1 Hz collocated SWH for Jason-3 and Jason-2, which show remarkable agreement. The regression line is very close to the unity. The bias is less than 2 mm and the RMSD is about 19 cm. The right plot shows a symmetrical distribution of the SWH RMS which indicates similar precisions.

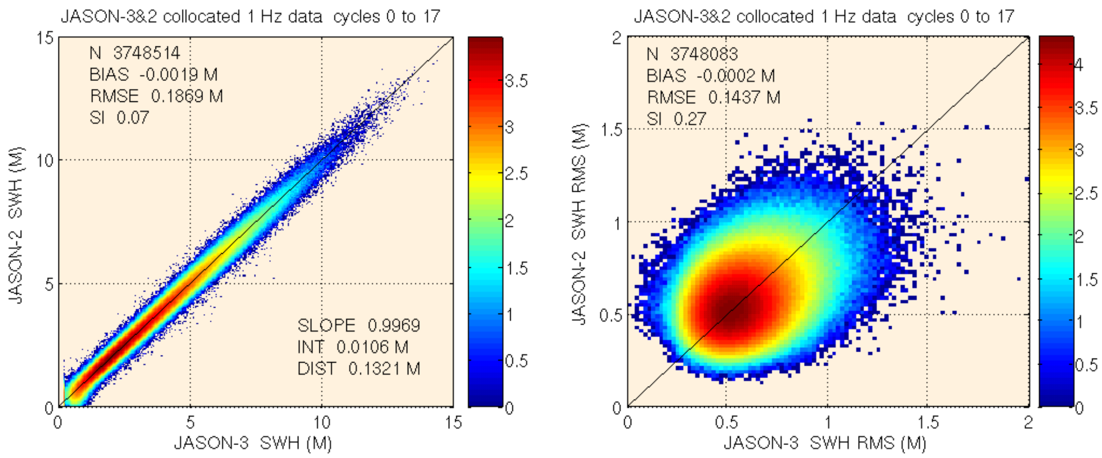

Figure 10: JASON-3 and JASON-2 1-Hz collocated SWH (left) and SWH RMS (right) (SWH RMS filtering applied). Extracted from Queffeulou [3].