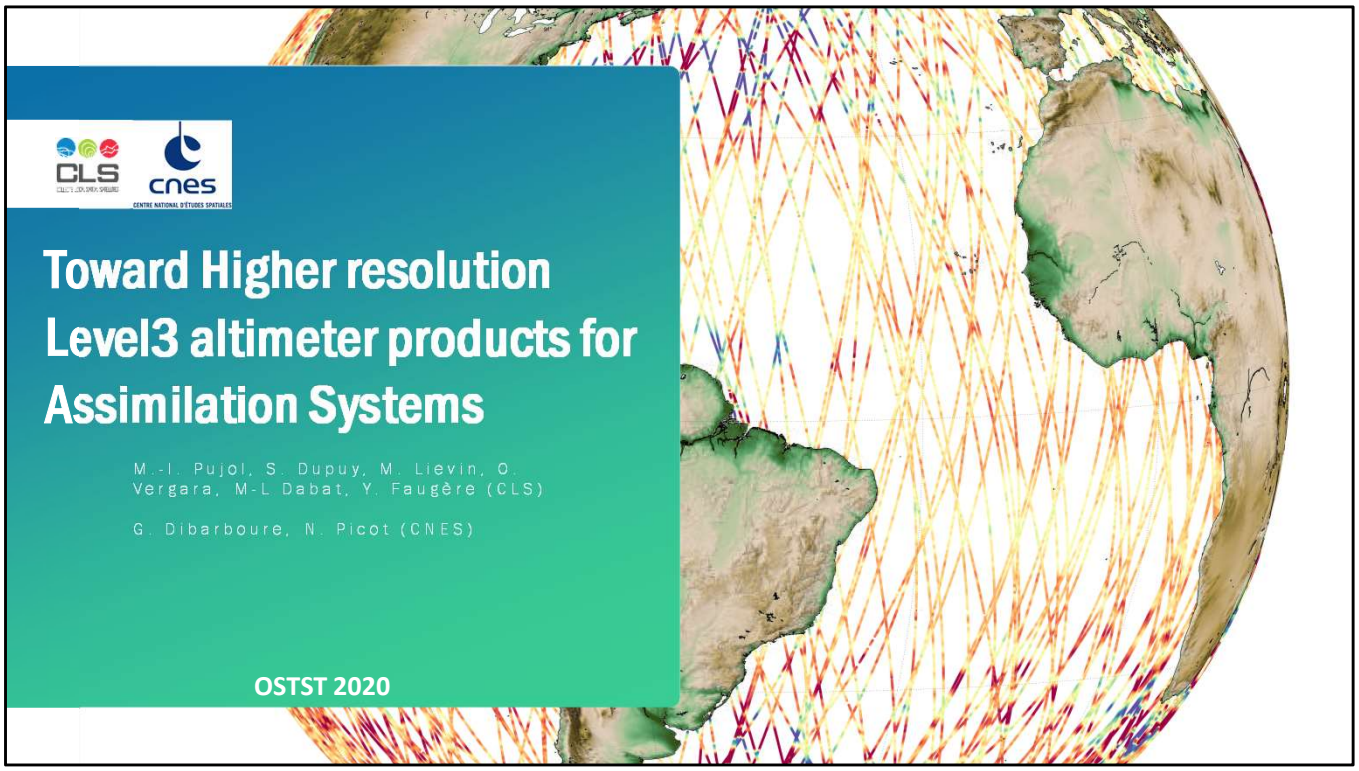


We present in this document Level-3 (L3) along-track, cross-calibrated altimeter products with a sampling and resolution improved compared to the conventional 1Hz product.

Motivations

- Answer the users need & Copernicus Marine Service (CMEMS) requirement:
  - Toward higher resolution model in open ocean and coastal areas: model resolution increased by a factor 3 or more in the post 2025 period.
    → need higher resolution altimeter products to constraint them (P-Y Le Traon, OceanPredict 2019)
  - For regional applications/models
  - Downstream applications: marine safety; biogeochemical activity; Research activities

➔ Advance in altimeter processing, including necessary noise reduction, allow us to increase the along-track product resolution and better resolve small mesoscale signal

Our first motivation to work on such L3 product is the Copernicus Marine Service (CMEMS) users need. First users in CMEMS are modelers. With the coming increase of the model resolution, they need higher resolution observation to constraint the models via the assimilation.
Recent advances in altimeter technologies and processing allow us to work on development of a higher resolution L3 altimeter product. Indeed, our first limitation is the residual noise that dominate a short wavelength. With new SAR technology and new retracking and corrections recently developed, we now can reach acceptable noise level to observe wavelengths up to ~30km.

Motivations

- Currently processed in R&D context (CNES funding)
  - V1 version of 5Hz samples delivered in 2018 on AVISO+

    Objectives : demonstrate the added value of the higher sampling (5Hz (~1,3 km) instead of 1Hz (~7km). Benefits from High Frequency Adjustment (HFA) correction for noise reduction.
  - V2 version delivered in June 2020 on AVISO+

    Objectives:
    - Better resolve the small mesoscale structures → use up-to-date geophysical corrections and innovative altimeter processing able to reduce noise & short wavelengths errors
    - Fix some anomalies detected in the v1 samples, improve the processing → mainly editing anomalies (no tuned editing for ice areas; over editing near the coasts for LRM; …)
    - Consolidate the design of the processing for a future operational production.
- Aims to be implemented in CMEMS operational production in 2021

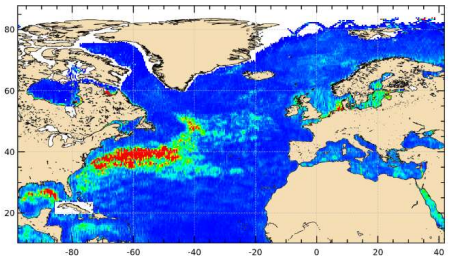
This work was done thanks to CNES funding.
It started in 2017-2018 with the development of a first version (V1) of L3 product sample, delivered with a 5Hz sampling. This version of the product is quite close to the conventional 1Hz products available on CMEMS. Only a High Frequency Adjustment (HFA) correction was applied on LRM measurement in order to reduce the residual noise and access to small mesoscale.
More recently, a second version (V2) of the sample was delivered. It includes various new processing/corrections that contribute to better resolve the small mesoscale signal, both on SAR and LRM measurements
Such products aim to prepare the future generation of operational altimeter products that will be disseminated in CMEMS.

L3 5Hz samples v1

Available on AVISO+

- Delayed Time L3 along-track products
- Deduced from 20Hz upstream products
- Delivered with a 5 Hz sampling: good compromise between observing capabilities and sampling needs
- Defined over the North Atlantic Area, including Med and Black Sea
- Altimeter standards and corrections homogeneous with contemporaneous 1Hz products + noise reduction processing (derived from Zaron et DeCarvalho. [2016] methodology) applied on LRM measurements
- Different physical variables available:
  - Access to essential geophysical corrections currently removed from altimeter measurement and that can be used to change the physical content of the SLA
  - Estimation of across-track geostrophic currents

Mission		Start date L3	End date L3
Jason-2	J2	2015-01-01	2016-02-29
Cryosat 2	C2	2015-01-01	2015-12-31
Altika	AL	2015-01-01	2017-02-03
Jason-3	J3	2016-03-28	2017-03-29
Sentinel-3A	S3A	2016-04-06	2017-04-17



North Atlantic:
Latitudes (min/max) -> 10° North / 88° North
Longitudes (min/max) -> 98° West / 42° East

We present on this slides the main characteristics of the V1 version of the samples L3 5Hz.
The Sea Level Anomaly (SLA) and other essential variables are delivered with a 5Hz sampling. This sampling was retained as a good compromise between the current altimeter observing capabilities and users needs.
The processing uses in upstream the full rate (20Hz) altimeter measurement.

L3 5Hz samples v1

SLA low pass filtered in order to reduce noise measurement:

- Methodology based on the SLA spectral content analysis over the Europe area
- 20Hz noise used for SAR measurement and reduced 1Hz bump measurement
- Different cut-off wavelength applied according to the altimeter considered

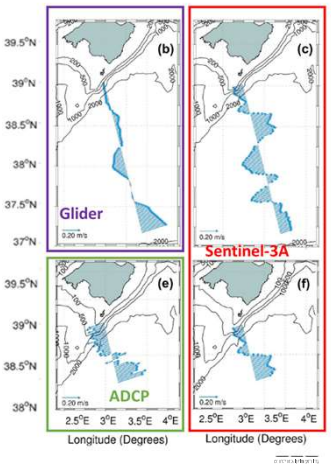
	North Atlantic Area
AL	30 km
S3	30 km
J3	35 km
C2	35 km
J2	35 km

Cut-off wavelengths used for 5Hz V1 processing

➔ Cut-off wavelength defined for Sentiel-3A consistent with independent study (Heslop et al, 2017):

30 km low-pass filter for the Sentinel-3A data was sufficient to remove the high-frequency noise while still providing a more accurate view of the mesoscale features in the WMED than previously possible

Across-track absolute Geostrophic Velocity along S3 track



We estimated the observable wavelength limit through an analysis of the spectral content of the SLA. The signal to noise ratio (SNR) = 1 was considered.
We retained the observable wavelengths around 30 to 35km. These values are quite representative of the observing capability over the Mediterranean Sea and Black Sea : in good agreement with an independent study done by Heslop et al (2017) in the Balearic Sea. But they certainly are too optimistic in the Atlantic Ocean, were higher significant wave heights (SWH), that contribute to increase the noise measurement, can be observed.

references:

Heslop E.E, A. Sánchez-Román, A. Pascual, D. Rodríguez, K. A. Reeve, Y. Faugère, M. Raynal (2017). Sentinel-3A Views Ocean Variability More Accurately at Finer Resolution. Geosph. Res. Letter 44 (24), 12,367-12,374. https://doi.org/10.1002/2017GL076244

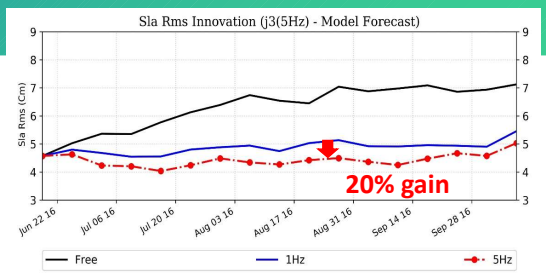
Example of application

Courtesy of Mounir Benkiram (MOi)

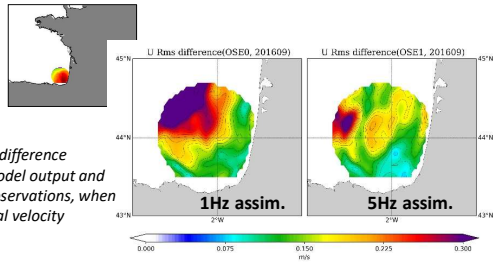
Test impact of the 5Hz altimeter products assimilation into the CMEMS IBI model with 1/36° spatial resolution :

➔ the high-resolution products significantly improve the model performances:

- Higher resolution SLA assimilation impact at mesoscales → visible on SLA increments
- Model SSH forecast improved → better consistency between model forecast and observations: 20% gain
- Positive impact on other variables → modelized SST better in accordant with observations when assimilation 5Hz altimeter products rater than 1Hz
- Better consistency between model output and independent measurement



SLA innovation temporal evolution (difference between observation and model forecast) for model free run (black) and model assimilated with 1Hz (blue) or 5Hz (red) altimeter measurement



RMS of the difference between model output and HF radar observations, when model. Zonal velocity component.

The L3 5Hz V1 sample was used for assimilation in a high resolution (1/36°) regional model defined over the Iberian-Biscay Irish-Ocean (courtesy of Mounir Benkiran, MOi). Compared to the assimilation of the conventional 1Hz product, the assimilation of the L3 5Hz leaded to a significant reduction of the model errors, especially at mesoscale: nearly -20% reduction of the innovation of the SLA (rms of the differences between the model forecast and observations). A better consistency with independent in-situ observation is also observed. We present here for instance the comparison between the zonal velocities modelized in the bay of Biscay and observed with a high frequency radar: the rms of the differences is significantly reduced when the model assimilate L3 5Hz products rather than conventionnel 1Hz.

L3 5Hz samples v2

Use resent progress done in altimeter processing:

- LR-RMC processing (Boy et al, 2017) that contributes to reduce the swell impact compared to the SAR processing
- Adaptive processing (Thibaut et al, OSTST 2017) that reduces the noise and bump on LRM measurements
- HFA empirical correction (Zaron et DeCarvalho, 2016; Tran, 2019): reduction of the noise measurement signature
- Updated HMP estimation along S3A tracks (Dibarboure & Pujol, 2019): reduction of the MSS errors at short wavelengths

Now, different progresses have been done in the altimeter processing and corrections applied. We considered the different improvement listed to construct a V2 version of L3 5Hz samples: All of them contribute to reduce altimeter errors at short wavelength (< ~50km).

L3 5Hz samples v2

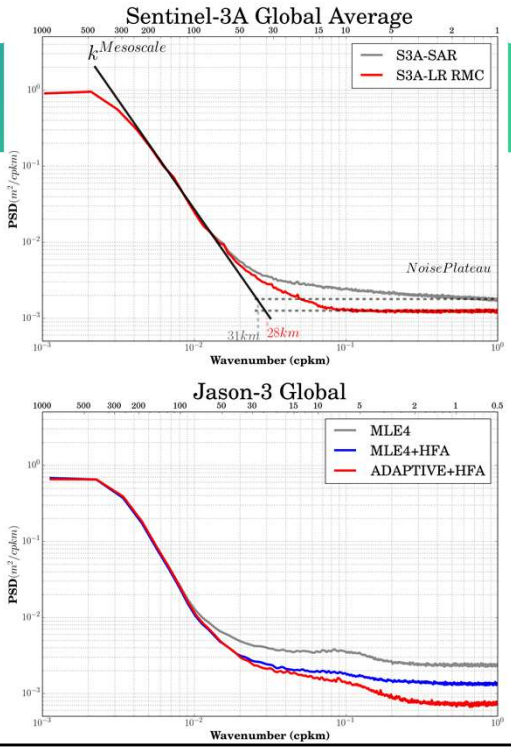
Sentinel-3A LR-RMC benefits (Moreau et al, 2020):

- Reduced noise measurement
- Reduced SWH & swell impact (→ red noise)

Jason Adaptive + HFA benefits (Thibaut et al, 2017; Tran et al, 2019):

- Reduced noise measurement
- Reduced spectral hump

→ we expect to better resolve the smallest scales compared to conventional SAR and LME4 processing



We illustrate here the impact of:

- the LR-RMC processing applied on the SAR measurement (Sentinel-3A) : reduction of the measurement noise by nearly 20% compared to the conventionnal SAR rocessing. It also contributes to reduce the red color of the noise with a reduced dependancy to the wave and swell signal (Moreau et al, 2020).
- The Adaptive retracking and HFA correction applied on LRM Json-3 measurement : the Adaptive processing allows to reduce the SSH measurement noise by at least 10% (Thibaut et al, 2017), while the HFA and 2D-SSB corrections contributes to the reduction of short wavelength errors (< 50km; including spectral hump and noise) up to ~25% (Tran et al, 2019).

references:

Moreau T., E. Cadier ,F. Boy, J. Aublanc, P. Rieu, M. Raynal, S. Labroue, P. Thibaut, G. Dibarboure, N. Picot, L. Phalippou, F. Demeestere, F. Borde,C. Mavrocordatos.(2020). High-performance altimeter Doppler processing for measuring sea level height under varying sea state conditions. In Prep.

Thibaut P., J.-C. Poisson, T. Moreau, A. Halimi, F. Boy, A. Guillot, S. Le Gac, N. Picot, Convergent solution for retracking conventional and Delay Doppler altimeter echoes, OSTST 2017, Miami, USA

Tran N., D. Vandemark, E. D. Zaron, P. Thibaut, G. Dibarboure and N. Picot: Assessing the effects of sea-state related errors on the precision of high-rate Jason-3 altimeter sea

level data. Advances in Space Research": 25 Years of Altimetry, 2019.
https://doi.org/10.1016/j.asr.2019.11.034

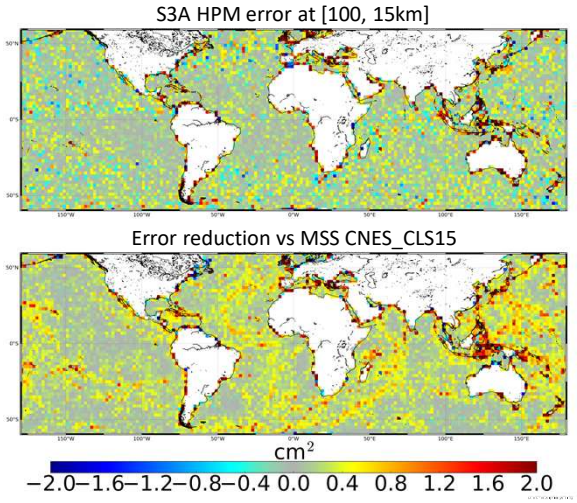
L3 5Hz samples v2

Refined estimation of the MSS solution along Sentinel-3A tracks (HMP):

- Benefit of the LR-RMC processing to reduce the noise → we expect to better resolve small scales
- Benefit of extended temporal period (~2.5 years) vs the first version of the HMP presented by Dibarboure & Pujol (2019)

→ HPM errors at WL [100, 15km] : 0,12 cm² (10% of the estimated noise free SLA variance)

→ Reduction of the MSS errors by more than 70%



The Sentinel-A processing also includes he use of a refined Mean Sea Surface estimation along the track of the altimeter, also called Hybrid Mean Profile (HMP). A specific HMP was estimated in consistency with the LR-RMC processing applied on the L3 Hz V2 processing, following the methodology described in Dibarboure et Pujol (2019). The HMP errors at short wavelengths is quite low (10% of the noise free estimated SLA variance). It allows to reduce the MSS (CNES_CLS_2015) error by nearly 70%. This reduction is mainly visible along bathymetric structures.

references:

Dibarboure G., M.-I. Pujol. (2019). Improving the quality of Sentinel-3A with a hybrid mean sea surface model, and implications for Sentinel-3B and SWOT. Advance in Space Res., https://doi.org/10.1016/j.asr.2019.06.018

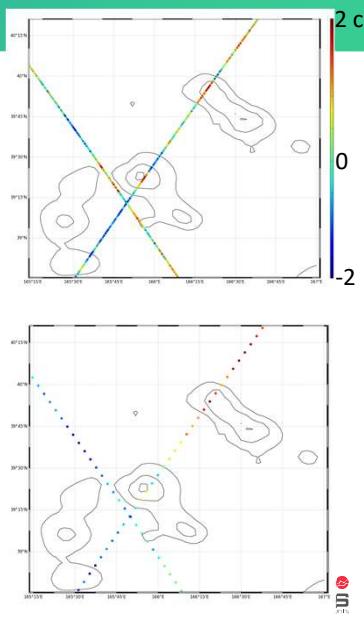
L3 5Hz samples v2

Refined estimation of the MSS solution along Jason-3 tracks (HMP):

Tests also show the capability of the full rate Jason-3 measurements to better resolve the MSS structure than the conventional 1Hz measurement.

- Benefit of the adaptive & HFA processing to reduce the noise
- Benefit of temporal period ~2.5 years

Note: Jason-3 HPM not used in L3 5Hz V2 processing



Differences between HMP defined along Jason theoretical tracks and a gridded Mean Sea Surface (CNES_CLS model). HPM deduced from 2,5 years of 20Hz Jason-3 measurement (top) and from ~14 years of Jason-1&2 1Hz measurements (bottom). Bathymetric contours [-5000,-4000,-3000m] (black lines)

Tests of computation of a HMP along ason-3 tracks has also be done using 20Hz measurements with adaptive and HFA processing. They show that with only 2,5 years of measurement used, this HMP allow us to capture more accurately the small MSS structures that are not or not accurately observed with the conventional 1Hz measurement, even cumulating a long temporal period to reduce as much as possible errors at short wavelengths.

The figure illustrates the observation of small bathymetric structures with the HMP computed on 20Hz Jason-3 measurement (top) and 1Hz Jason-1&2 measurements (bottom). Bathymetric structures of less than ~20km diameter, usually not accurately observed with the reference gridded MSS CNES_CLS_15, are well observed in 20Hz (positive anomaly compared to the reference gridded MSS); not so well with the 1Hz HMP.

Note that this HMP was not used in the L3 5Hz V2 sample processing.

L3 5Hz samples v2

Up-to-date geophysical & environmental corrections:

- 2D SSB [Tran et al, 2019] for Jason
- FES2014b ocean tide solution
- Internal Tide signal [Zaron, 2019] included in geophysical corrections

Altimeter standards used for L3 5Hz samples V2 production.
Differences with V1 samples

	Sentinel-3A	OSTM/Jason-2	Jason-3	SARAL/AltiKa	Cryosat-2
Orbit	GDR-E				
retracking	LR-RMC (with LUT correction)	Adaptive [Thibaut et al, 2017]	Adaptive [Thibaut et al, 2017]	LRM	SAR & LRM
Noise reduction	-	HFA adaptive [Tran 2019]	HFA adaptive [Tran 2019]	HFA [Tran 2018]	HFA [Tran 2018] (LRM)
Sea State Bias	Non parametric SSB [Tran 2015]	2D SSB [Tran 2019]	2D SSB [Tran 2019]	Non parametric SSB	Non parametric SSB
Ionosphere	Dual-frequency altimeter range measurement	Dual-frequency altimeter range measurement	Dual-frequency altimeter range measurement	GIM [Ijima et al., 1999]	
Wet troposphere	From AMR radiometer	From J3-AMR radiometer Neural Network correction (3 entries), [Fréry et al. in prep]	From J3-AMR radiometer Neural Network correction (3 entries), [Fréry et al. in prep]	Neural Network correction (5 entries) [Picard et al., in prep]	From ECMWF model
Dry troposphere	Model based on ECMWF Gaussian grids				
Combined atmospheric correction	MOG2D High frequencies forced with analysed ECMWF pressure and wind field [Carrere and Lyard, 2003; operational version used, current version is 3.2.0] + inverse barometer Low frequencies				
Ocean tide	FES2014b [Carrère et al., 2015]				
Solid Earth tide	Elastic response to tidal potential [Cartwright and Tayler, 1971], [Cartwright and Edden, 1973]				
Pole tide	[DESAI, 2017]				
MSS	HMP_2019	CNES-CLS-2015			
MDT	CNES_CLS18 (including SOCIB Med)				
IW	M2,K1,O1,S2 [Zaron 2019, HRET 7.0]				

We summarize here the main standards and corrections applied for the L3 5Hz V2 sample processing. Differences with the V1 version are underlined in red. A majoritu of them also correspond to differences with the conventional 1Hz processing currently on going on CMEMS.
The main differences are:

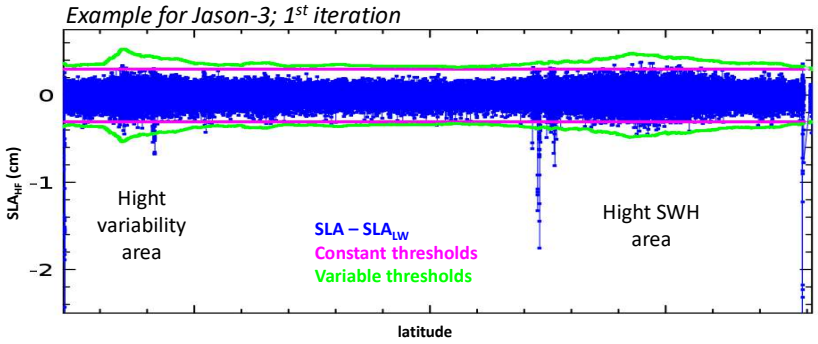
- the LR-RMC and adaptive processing discussed before
- the HFA and SSB corrections improved for Jason missions
- the internal tide correction now applied on the measurement
- The HMP used for Sentinel-3A processing

L3 5Hz samples v2

Improved valid data selection:

- Specific selection over ice areas using wave-from classification (Sentinel-3, AltiKa) and OSISAF
- Iterative editing taking into account modulation by high SWH and high ocean variability in thresholds definition

Example for Jason-3; 1st iteration



The processing used in the L3 5Hz V2 sample production also includes improved valid data selection.

- ice contaminated measurement were identified using a combination f the sea ice concentration (OSISAF) and waveform classification when available (Sentinel-3A and AltiKa)
- An iterative processing applied on SLA allow us to reject invalid measurement over ocean. The processing includes specific threshold modulation by ocean variability and SWH in order to take into account the higher signal variability and noise level in high variability and high SWH areas. The rate of rejected measurement is less important than when using a constant threshold criterion.

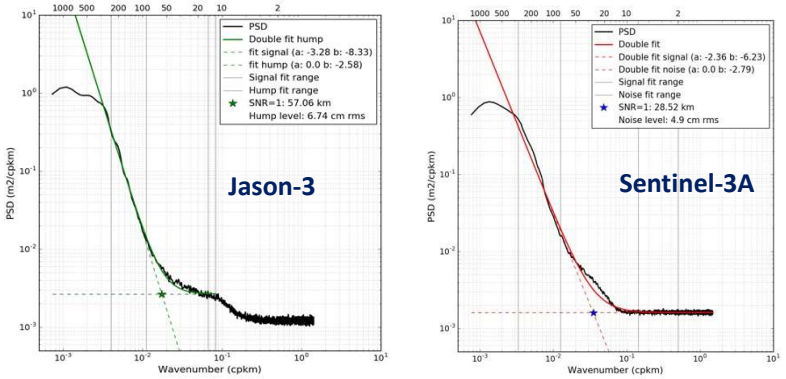
L3 5Hz samples v2

SLA observable wavelength and low-pass cut-off filtering definition :

Sentinel-3A	OSTM/Jason-2	Jason-3	SARAL/AltiKa	Cryosat-2
35	55	55	40	40

Cut-off wavelengths used in L3 5hz V2 (km)

- Defined by analysis of the spectral content over the Eastern North Atlantic Area, considering SNR=1.



SLA power spectrum density for Jason-3 and Sentinel-3A 20Hz measurements over the North East Atlantic region and for the [2018] period, processed for L3 5Hz V2 production

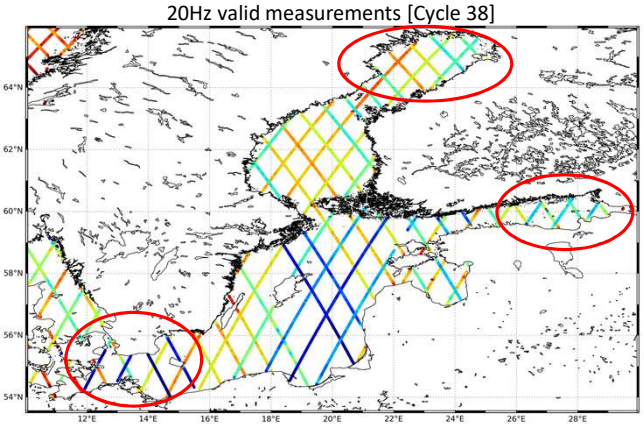
As for V1 version, the SLA is filtered inn order to remove short wavelength dominated by residual noise measurement.
The observable wavelength were defined considering the Eastern North Atlantic area.
The spectral analysis methodology applied iw defined by Vergara and al (2019). As for the V1 version, we considered the SNR=1.
The observable wavelengths reach between 35 to 55km depending on the altimeter considered. They remain lower for the SAR missions while the results obtained for LRM measurement are mainly induced by the residual spectral hump signature.
These values are representative of the annual mean situation and are probably pessimistic for enclosed Seas (Mediterranean, Black and Baltic Sea).

References:
Vergara, O., Morrow, R., Pujol, I., Dibarboure, G., and Ubelmann, C. (2019). Revised global wavenumber spectra from recent altimeter observations. J. Geophys. Res. doi: 10.1029/2018JC014844

L3 5Hz samples v2

Example of 20Hz data selection with Sentinel-3A: Globally better spatial coverage with 20Hz than with 1Hz valid measurements

20Hz valid measurements [Cycle 38]



1Hz valid measurements [Cycle 38]

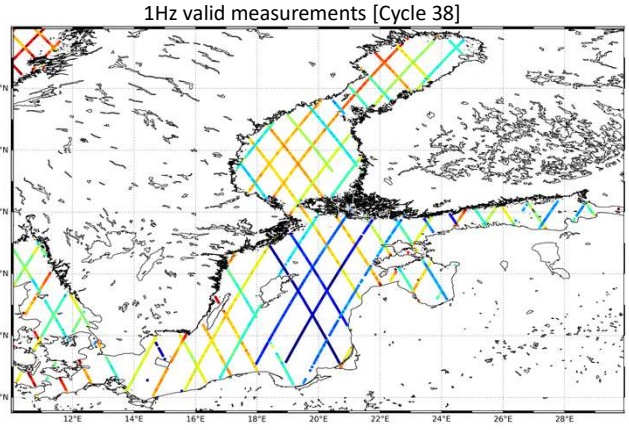
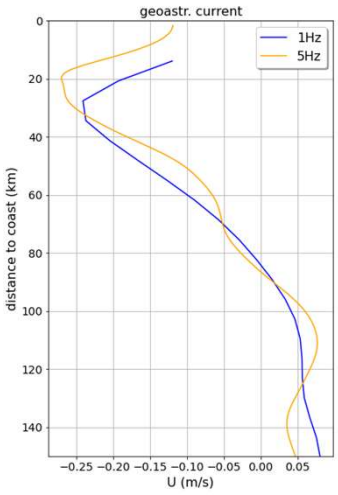
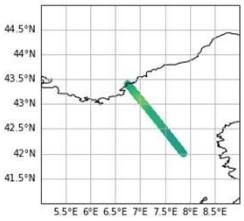


Illustration of the spatial coverage of the valid 20Hz vs 1Hz Sentinel-3A measurements over the Baltic Sea for cycle #38. Globally the rate of SLA availability with the 20Hz processing is higher, especially near the coast.

L3 5Hz samples v2





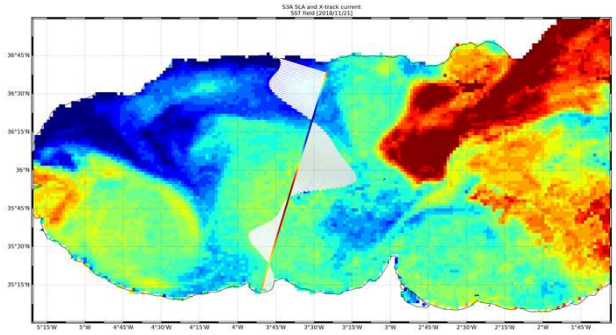
Examples of resolution of Liguro-Provincal current with L3 5Hz (V2) or conventional 1Hz product

Mean absolute geostrophic current along Jason-3A pass #222 over the [mid 2016, 2018] period. Result deduced from conventional L3 1Hz product (blue line) and 5Hz product (yellow line).

The pass location is given in the map.

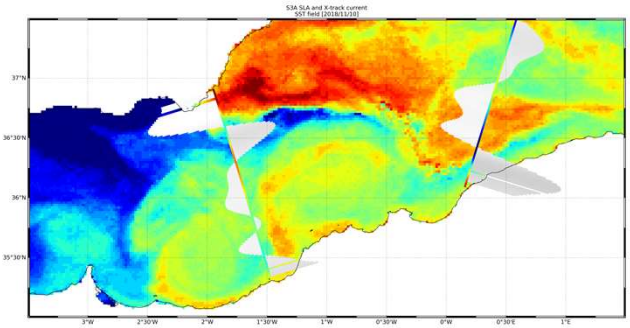
The quality of the L3 5Hz V2 product was analyzed in term of observability of specific coastal current. We focus here on the Liguro-Provincal current observed with Jason-3 pass #222. The mean geostrophic current, computed over the [mid 2016, 2018] period is quite well observed with the 5Hz product with a maximal intensity near 25km for from the coast. The 1Hz conventional product also catch the current, but with lower intensity and lower resolution near the coast. The position is also slightly moved compared to the 5Hz product. This could be explained by the different processing applied, especially different SLA filtering (larger cut-off wavelength used in the conventional 1Hz processing).

L3 5Hz samples v2



SST field (backgroup map), Sentinel-3A 5Hz along-track SLA (colored dots) and across-track geostrophic current anomaly (gray lines). Map for day 2020/11/10 (right) and 2020/11/21 (top).

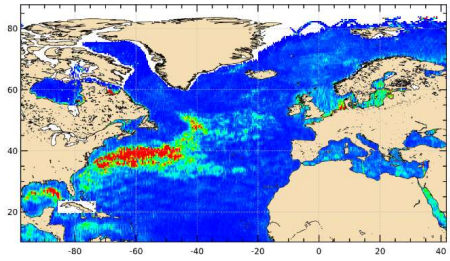
Examples of consistency between altimetry and SST field in November 2018



On other example in the Alboran Sea. Across-track current estimated from 5Hz products is in accordance with satellite SST color and capture quite well thin currant tongue.

L3 5Hz samples v2

- **Missions**: Jason-3; OSTM/Jason-2, Sentinel-3A, SARAL-DP/AltiKa, Cryosat-2
- **Period** : [Jul. 2016, Dec. 2018]
- **Area:** North Atlantic + Arctic Area (lat > 50°N)
- **Content:** SLA low-pass filtered, essential geophysical corrections (ocean tide, IW, DAC, LWE), across-track geostrophic currents, MDT



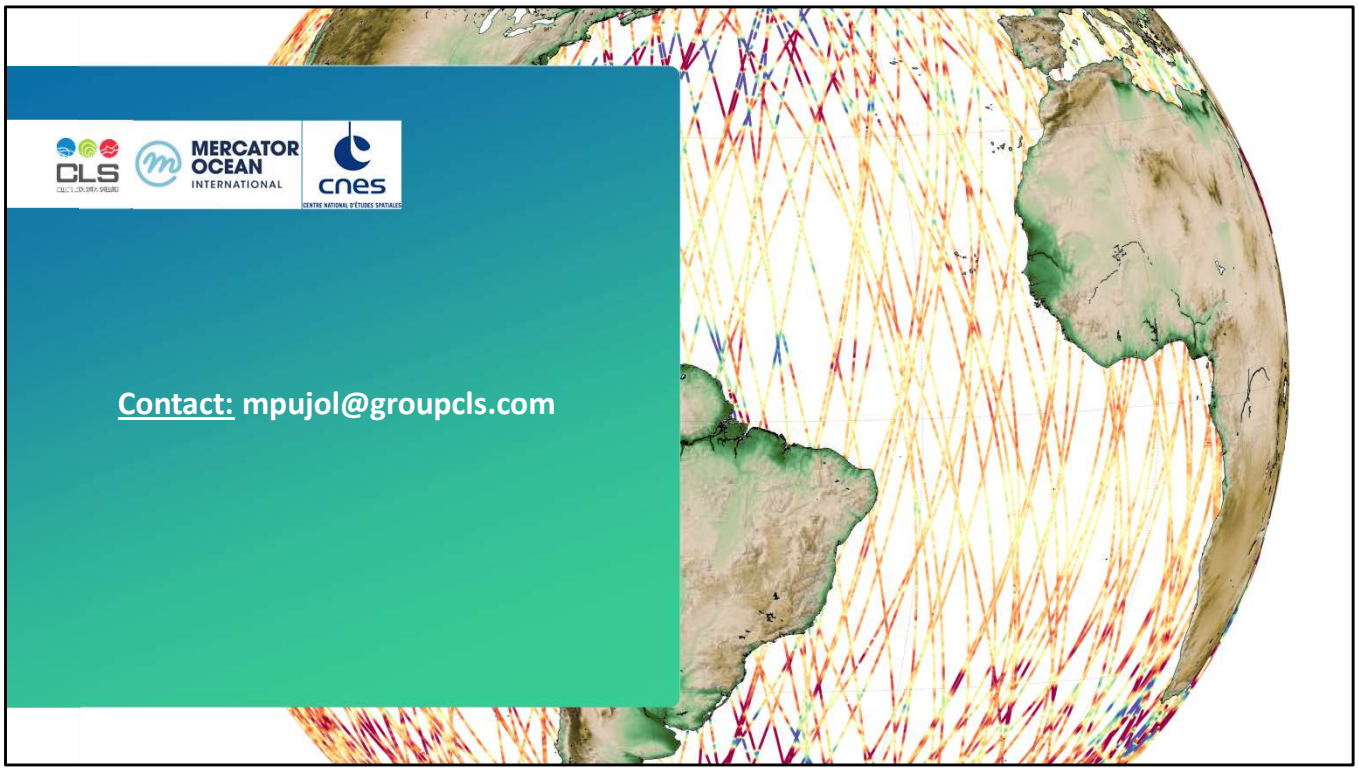
➔ **Available on AVISO+**

conclusions

We are working on the development of a L3 along-track product able to observe the small mesoscale signal (> ~30km). Samples with 5Hz (~1,3km) sampling are delivered on AVISO+

➔ First dedicated for regional applications, but could also be of interest for coastal applications (> ~10km) ➔ do not hesitate to test them and give your feedback (content, quality, sampling, …): always valuable to improve the products!

➔ The transition toward an operational production is foreseen in the coming years


CLS
MERCATOR OCEAN INTERNATIONAL
cnes
CENTRE NATIONAL D'ÉTUDES SPATIALES
Contact: mpujol@groupcls.com