AVISO+
Satellite Altimetry Data

#18

March 2021

Users Newsletter

SUMMARY

Jason-CS/Sentinel-6

towards a fourth decade of sea level observation

Pierre Buzon, Christian Jayles and Gilles Tavernier, CNES

The **Jason-CS/Sentinel-6 Michael Freilich** satellite, named after Dr. Michael Freilich, Director of NASA's Earth Science Division from 2006 to 2019, was successfully launched on 21 November 2020 from Vanderberg by a SpaceX Falcon9 rocket.

This is the 8th in-flight satellite of the Copernicus constellation and the first of the new Jason-CS/Sentinel-6 series dedicated to the continuous measurement of ocean topography and the climate, taking over from the emblematic altimetric TOPEX/Jason series.

The payload instruments were successively switched on, including DORIS on 25 November and Poseidon-4 on 29 November. DORIS on-board navigation converged in less than 4 hours as shown by the monitoring of the navigation quality index (Figure1).

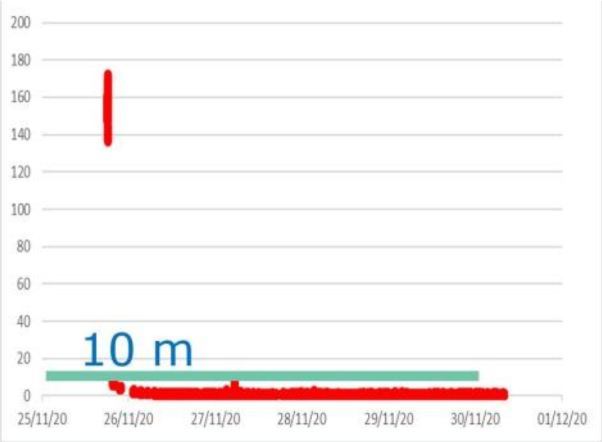


Figure1: Navigation quality index after DORIS switch-on. Credits CNES.

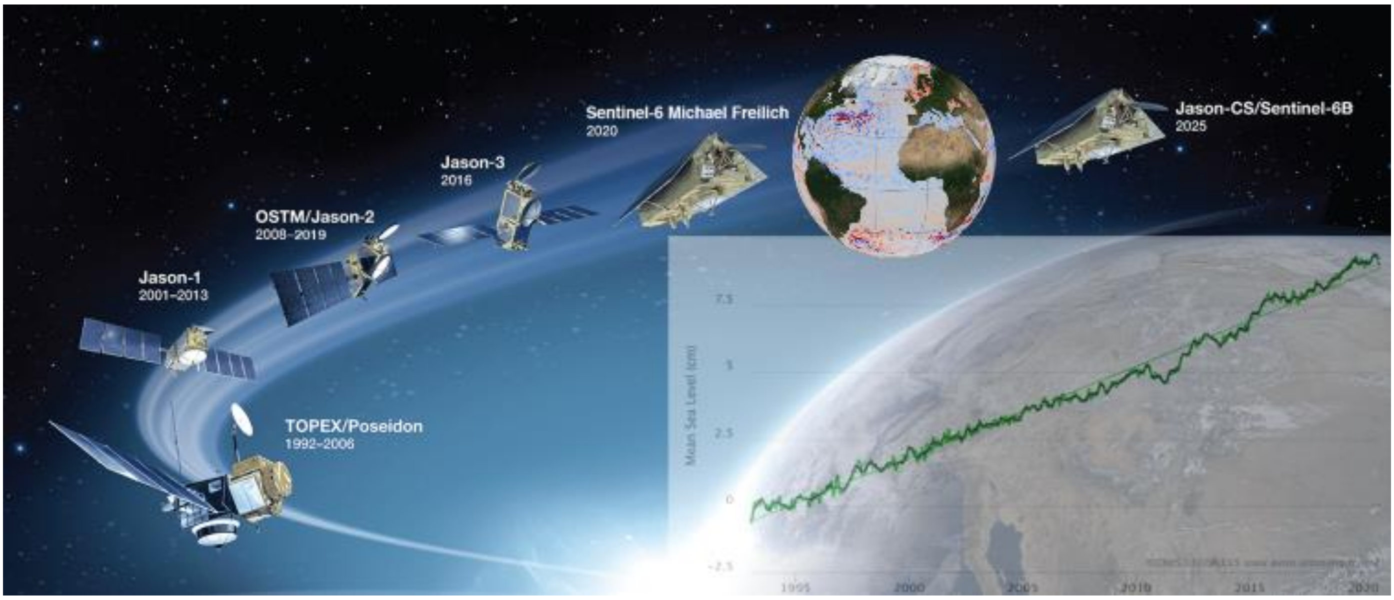


Figure2: Ocean topography missions and mean sea level rise in centimetres since 1992 (trends and time serie) (© NASA, CNES,

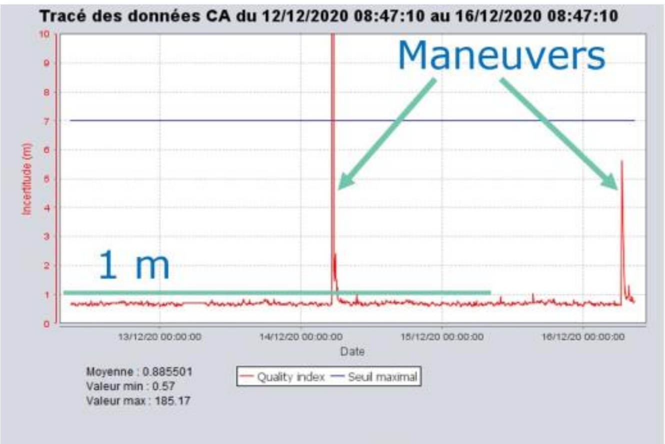


Figure3: Navigation quality index through manoeuvres. Credits CNES.

Figure5: RK410 mini-USO performance. Credits CNES.

The navigation quality index then remained around 60 cm, hardly disturbed by successive manœuvres (Figure3).

The brand new RK410 mini-USO quickly stabilised and demonstrated excellent performance (Figures 4 & 5).

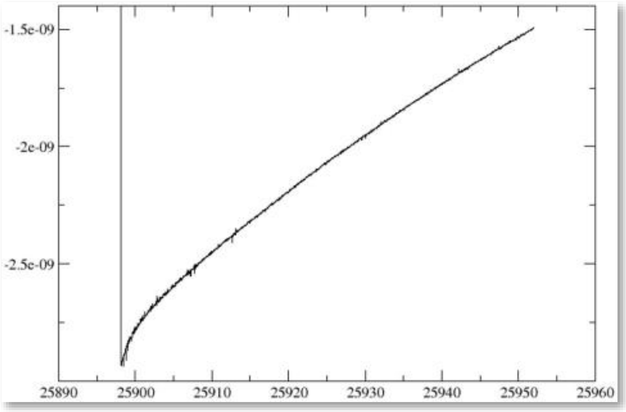


Figure4: RK410 mini-USO stabilisation after DORIS switch-on. Credits CNES.

On-board datation provided results similar to those of previous missions, which were better than 2 microseconds RMS (Figure6).

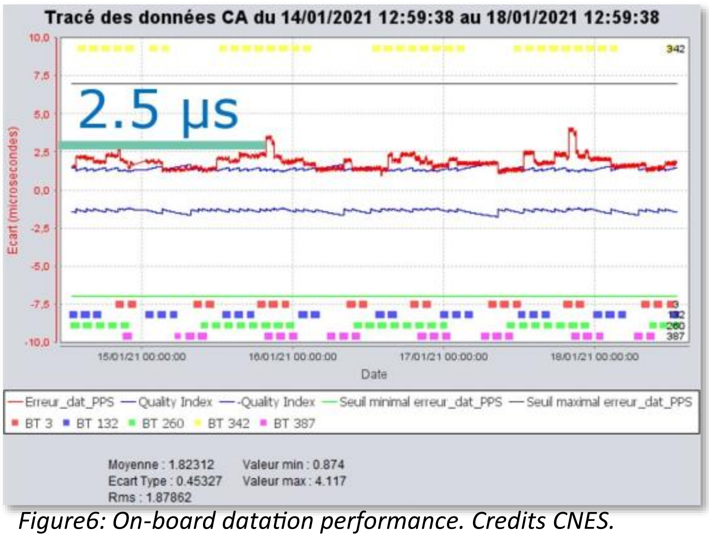


Figure6: On-board datation performance. Credits CNES.

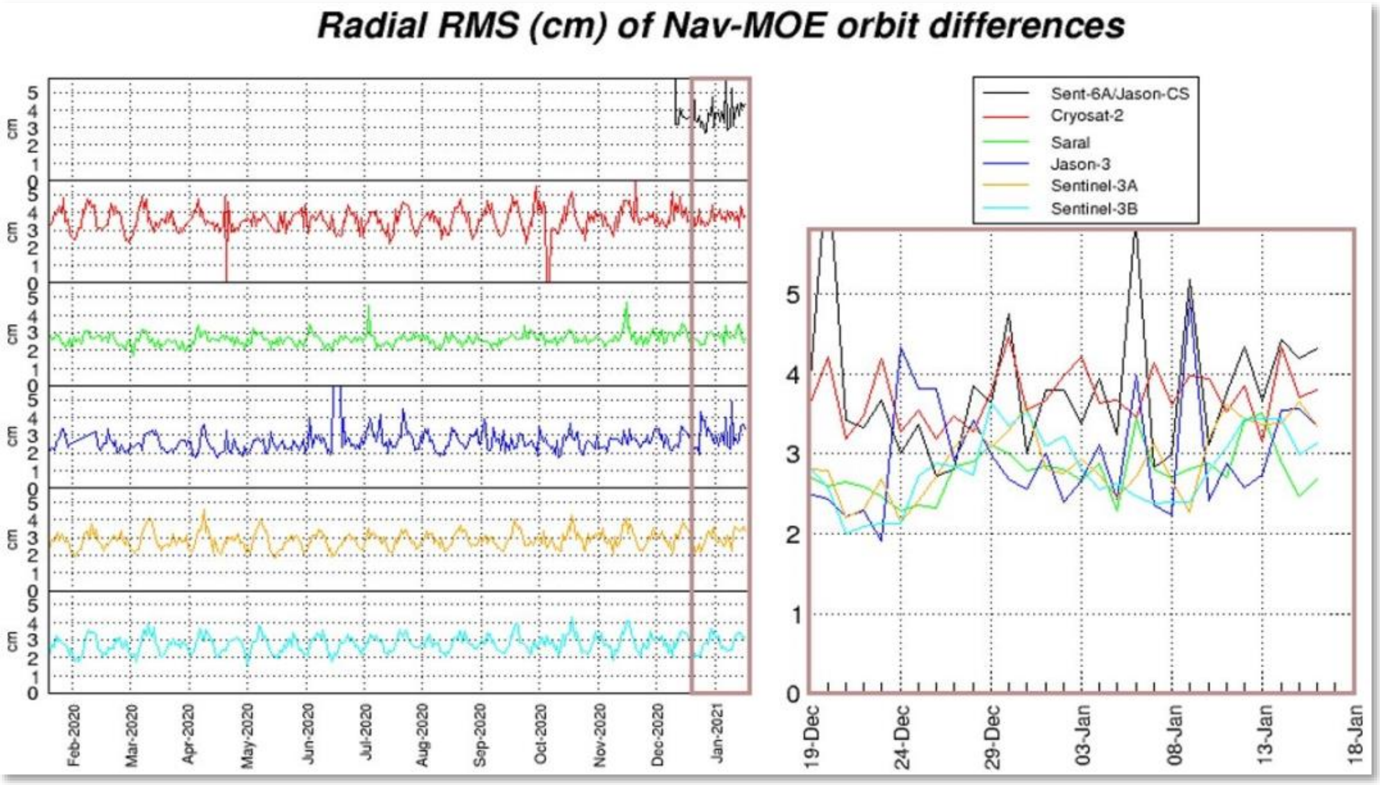


Figure7: On-board/MOE orbit comparison: radial component. Credits CNES, CLS.

The comparison of the orbit calculated on board with the MOE calculated on the ground shows an accuracy of the altitude calculation of a few centimetres, as for previous missions (Figure7 above).

On 18 December, Jason-CS/Sentinel-6 Michael Freilich reached the reference orbit of Jason-3, 30 seconds after it, for a tandem flight, beginning a calibration and validation phase that will last 12 months. Once this phase is complete, Sentinel-6 Michael Freilich will become the new reference mission replacing Jason-3, which will extend its mission to serve the scientific community and operational applications, on a new orbit chosen during 2021 among several possible options.

Analysis of the first measurements reveals that the satellite provides extremely accurate data, thanks to the digital architecture of Poseidon-4 and to the fact that, for the first time, two types of measurements, the conventional low-resolution measurements (LRM, low-resolution mode) and synthetic aperture radar (SAR) measurements, were carried out simultaneously. Low-resolution measurements will ensure continuity with previous missions, while high-resolution measurements should confirm a very promising potential in terms of the accuracy and fineness of the details observed.

Preliminary results have been disseminated by ESA (link) and EUMETSAT (link).

The satellite in-orbit verification checkpoint took place on January 26 and 27. All tasks were completed and most of the corresponding data were collected, allowing analyses of the results to be carried out and the final report to be prepared, with a delivery planned for the beginning of March.

A continuous basis with Sentinel-6B

After the launch of Sentinel-6A on 21 November 2020, its twin, Sentinel-6B, currently being integrated by Airbus Defence and Space in Friedrichshafen, should join it and take over in 2025 at the earliest. The essential measurement of the mean sea level rise, which is the result of human-induced global warming, can thus be continued on a continuous basis. Due to the melting ice and thermal expansion, rising sea levels have become a powerful reminder of how quickly humans change the climate. Following the TOPEX/Poseidon and Jason missions, the Jason-CS/Sentinel-6 series continues to take the pulse of global climate change.

Figure8: Artist impression of the Jason-CS/Sentinel-6 satellite. Credits NASA.

Climate indicators from space: ocean heat uptake and earth energy imbalance

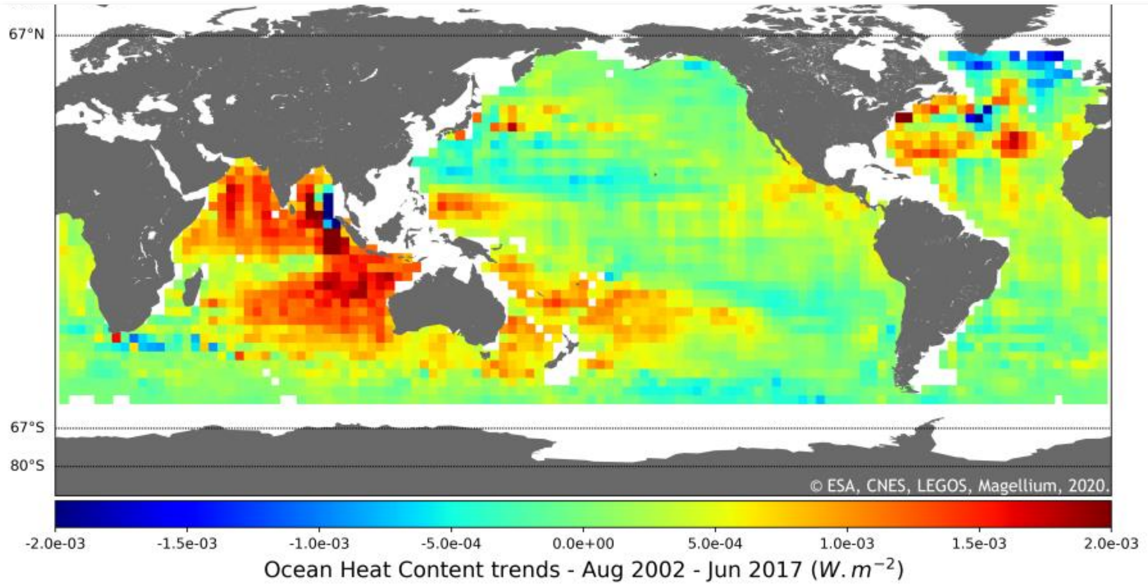
Florence Marti, Magellium

Over the past decades, anthropogenic emissions of greenhouse gases in the atmosphere have reduced the energy emitted by the Earth towards space. Now the Earth emits less energy towards space than it receives from the sun, leading to a radiative imbalance at the Top Of the Atmosphere (TOA). This **Earth Energy Imbalance** (EEI) is responsible for the accumulation of heat in the climate system, making it the primary cause of climate change. It is critical, therefore, to monitor the EEI to evaluate the amount of energy accumulating in the system and understand how this energy is causing the climate to change.

EEI can be estimated through an inventory of heat changes in the different reservoirs of the climate system – namely the atmosphere, the land, the cryosphere and the ocean. As the ocean concentrates the greatest proportion of the energy excess (~93%) in the form of heat, global variations in **Ocean Heat Content** (OHC) place a strong constraint on EEI estimates.

From the Ocean Heat Uptake…

The OHC variations can be estimated directly from net ocean surface heat fluxes measured based on Clouds and the Earth's Radiant Energy System (CERES) space measurements, from *in situ* data observed by the ARGO floats or from ocean model re-analyses. For the first time, **we estimate here the OHC using an alternative method based on spatial altimetry and gravimetry observations**, which complements these other approaches and is very promising for reducing uncertainty estimates.

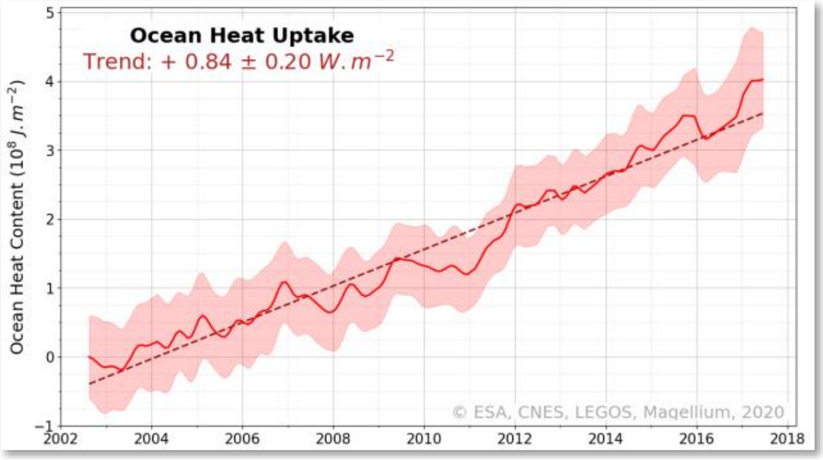


Using the "altimetry-gravimetry" method, global OHC variations (also called the ocean heat uptake) were retrieved from August 2002 onwards (corresponding to the initial GRACE data). Regional map of the OHC trends between August 2002 and June 2017 are shown here. Credits ESA, CNES, LEGOS, Magellium, 2020.

Measuring the EEI is challenging because it is a globally integrated variable whose variations are small (0.5–1 W.m^{-2}) compared to the typical annual and year-to-year variations of energy fluxes in and out of the climate system (incoming solar radiation is about 340 W.m^{-2}). Ideally, we would need EEI estimates with an accuracy of approximately ±0.1 W.m^{-2} at decadal time scales to be able to monitor not only the EEI variations caused by greenhouse gas (GHG) emissions but also those caused by volcanic eruptions or internal variability (such as the Hiatus). This pushes the challenge even further.

The OHC is estimated by measuring the thermal expansion of the ocean based on differences between the total sea level content derived from altimetry measurements and the mass content derived from gravimetry data, a method known as "***altimetry-gravimetry***".

This "***altimetry-gravimetry***" approach provides consistent spatial and temporal sampling of the ocean, covering nearly all the global oceans, except for polar regions where the sea is completely covered by sea ice (essentially north of 80°N), and it provides estimates of OHC variations over the ocean's entire depth.



The temporal evolution of the global ocean heat uptake retrieved from the "altimetry-gravimetry" space data shows an increase of +0.84 W.m^{-2}, which accounts for approximately 93% of the EEI. The curve is filtered out for 6-month signals and the envelope error is computed at 1.65-sigma (i.e., with a 90% confidence level), together with the uncertainty on the slope.

Credits ESA, CNES, LEGOS, Magellium, 2020.

...to the Earth energy imbalance

The EEI indicator is derived from the temporal variations of the ocean heat content, that is by calculating its derivative (called the ocean heat uptake). Energy uptakes from the land, cryosphere and atmosphere reservoirs represent about 7% of the EEI and are not accounted for. The average value of the EEI is +0.84 W.m^{-2} with an error of +/- 0.2 W.m^{-2} (with a 90 % confidence level) and shows that on average the Earth stores energy. This EEI value represents an enormous amount of energy when it is integrated into the entire Earth's surface at the top of the atmosphere (20 km) since the EEI represents a total Earth energy uptake of approximately 430 TW (i.e., about 1 000 times the global nuclear power capacity).

The results show that on average the **Earth stores energy.** Clarifying the uncertainties on the EEI indicator will help address the question of the significance of EEI variations.

The development of accurate climate indicators based on space data would also help better understand the Earth energy budget, and how and on what time scales energy is stored in the different reservoirs. Policymakers could rely on the EEI to monitor the impact of tough political decisions in terms of GHG emissions. To what extent would the changes in GHG emissions brought about by an oil crisis or a global health crisis like the 2020-2021 pandemic be visible in such an indicator?

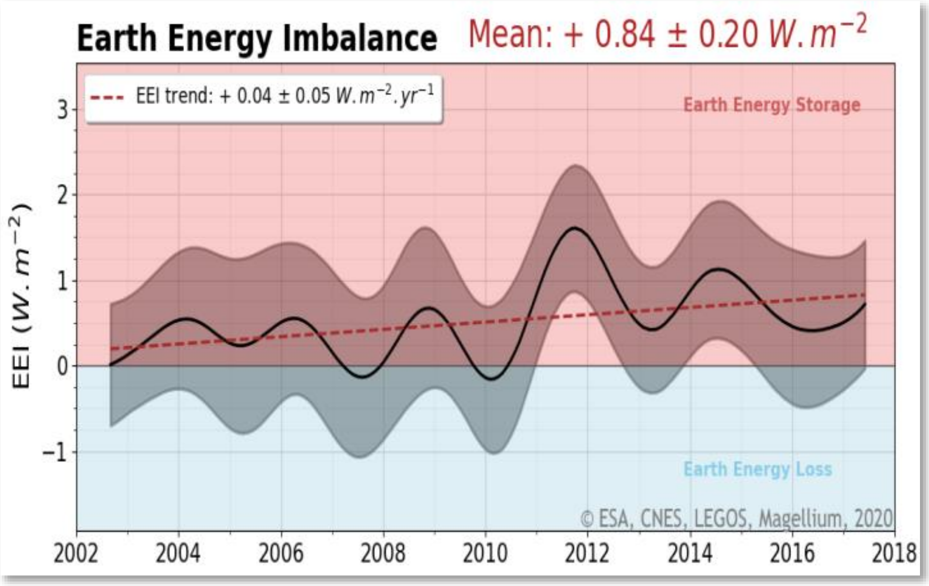
Access to the product

The OHC-EEI product is described and can be downloaded freely on AVISO+. Users will mainly be interested in ocean heat content time series at regional (grids) and global scales, and Earth energy imbalance time series.

This work was supported by ESA through the MOHeaCAN project (Monitoring Ocean Heat Content and Earth Energy ImbalANce from Space). The dissemination of this product through the **ODATIS Ocean Cluster** and future changes to the product are supported by CNES.

References

Meyssignac, B., et *al.* (2019): Measuring Global Ocean Heat Content to Estimate the Earth Energy Imbalance, Front. Mar. Sci., 6, doi:10.3389/fmars.2019.00432.



The temporal evolution of the Earth energy imbalance is estimated by monitoring the variations of global ocean heat uptake. The global ocean heat uptake was first filtered out for signals lower than 3 years. The envelope error is computed at 1.65 (i.e., with a 90% confidence level), together with the uncertainty on the slope, which corresponds to the acceleration of ocean heat uptake. Credits ESA, CNES, LEGOS, Magellium, 2020.

Towards high-resolution gridded Sea Surface Height products

Maxime Ballarotta, CLS— Emmanuel Cosme, IGE

The **Surface Water and Ocean Topography** (SWOT) mission, scheduled for launch in 2022, will provide 120-km wide images of Sea Surface Height (SSH) at a kilometric resolution, i.e., ~10 times the resolution of current nadir-looking technologies. To prepare for the SWOT era, researchers from CNES/CLS, IGE/MEOM, Ocean-Next, and IMT-Atlantique are investigating **how to build high-resolution gridded SSH products** from space altimetry, using present-day nadir altimeters and the future SWOT mission.

Maps of the ocean surface topography historically distributed by AVISO+, now available on the Copernicus Marine & Environmental Monitoring Service, rely on the DUACS system developed by CNES and CLS. The current DUACS system processes constellations from 2 to 6 nadir-looking altimeters and is based on a **static linear (statistical) interpolation**. DUACS delivers daily SSH maps on a grid resolution of 1/4°, resolving scales larger than 200 km (Ballarotta et *al.,* 2019). However, ocean motions at a finer scale play a significant role in the climate system and must be resolved as best as possible in the gridded products. The upcoming high-resolution SWOT mission is a fantastic opportunity to observe these small-scale dynamics and increase the resolution of gridded SSH products.

In collaboration with researchers from IGE/MEOM, Ocean-Next, and IMT-Atlantique, CNES and CLS are exploring new mapping methods based on **data assimilation** (DA) and **artificial intelligence** (AI) **techniques to increase the resolution of the SSH maps**. In 2020, after substantial research and development efforts, DA, AI and DUACS methods were finally tested with identical simulated altimetric observations and inter-compared using the same evaluation metrics, emphasising the capacity to reconstruct the small-scale dynamics. The first ocean data challenge was born…

An open-source benchmarking approach

A SSH mapping data challenge was organised in 2020 to evaluate the best reconstruction sequences of Sea Surface Height (SSH) maps from partial satellite altimetry observations. This data challenge followed an Observation System Simulation Experiment (OSSE) framework: "Real" full SSH maps are derived from a numerical simulation with a realistic, high-resolution ocean circulation model: the reference simulation. Satellite observations

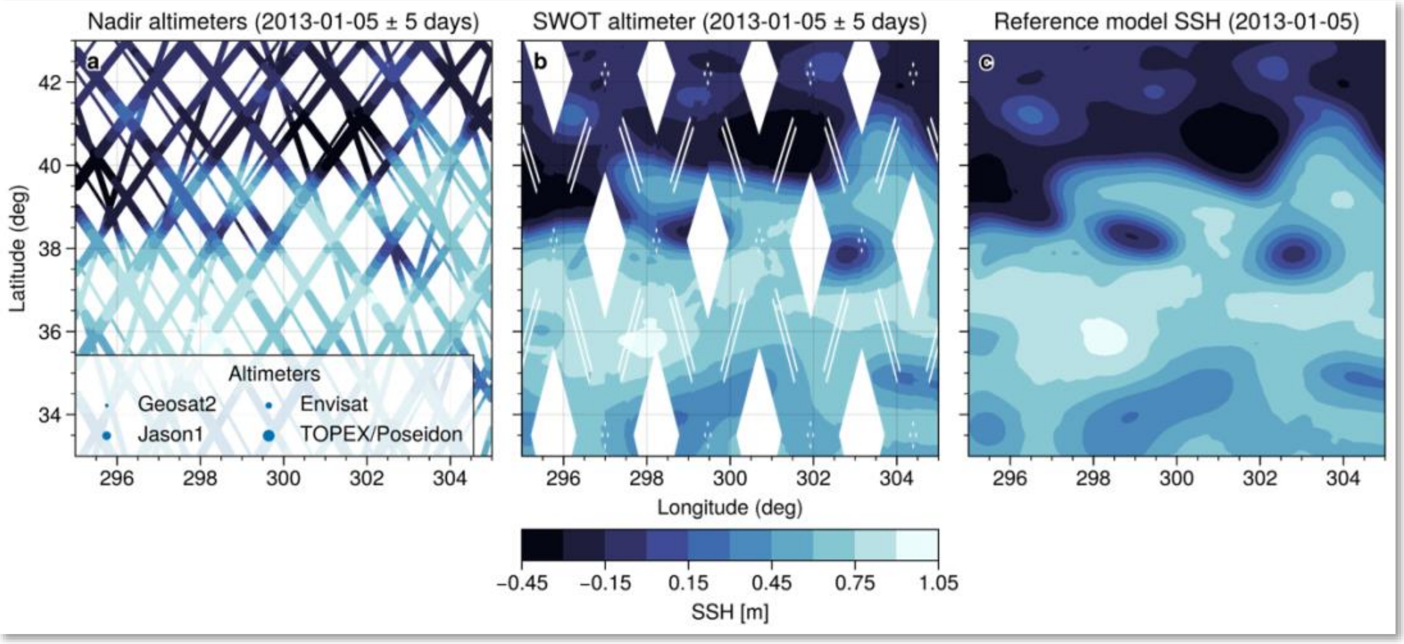


Figure 1: Example of simulated satellite observations: a) nadir altimeters and b) SWOT-like instrument. These pseudo-observations are sampled from the reference simulation in c). Credits: CLS/IGE.

are simulated by sampling the reference simulation based on realistic orbits of past, existing, or future altimetry satellites (Figure 1). The region of interest covers a 10° by 10° domain of the Gulf Stream region.

The data challenge is presented and publicly available for potential users/challengers on the ocean-data-challenges repository website. The **repository includes source codes, notebooks, access to data, and a guideline to run a baseline mapping experiment and apply evaluation metrics.** Any user/challenger is free to test his/her own mapping algorithm with the same input data and compare it to the other mapping algorithms with the same evaluation metrics. The main results are summarised in the leaderboard (Figure 2), which is also available on the homepage of the project.

The designers of this data challenge are testing their own mapping algorithms. At this time, the operational DUACS mapping algorithm and a DA technique (Back-and-Forth Nudging, BFN) has been tested and compared under different observation scenarios. As shown in the leaderboard, **the DA method can reconstruct finer spatial and temporal scales** (with a gain of ~30% in spatial and temporal resolution) than the DUACS mapping system. AI-based methods are under development. Details on the DA and AI-based methods investigated in this study can be found in the peer-reviewed articles by Le Guillou et *al.* (2020) and Beauchamp et *al.* (2020).

A new dataset available on AVISO+

In addition to the material provided on the data-challenge repository, the model simulation and simulated satellite observation datasets used in this challenge are made available to the public on the AVISO+ website. A new section entitled "**OCEAN DATA CHALLENGES - SIMULATED PRODUCTS**" hosts the data and provides a manual and references for users.

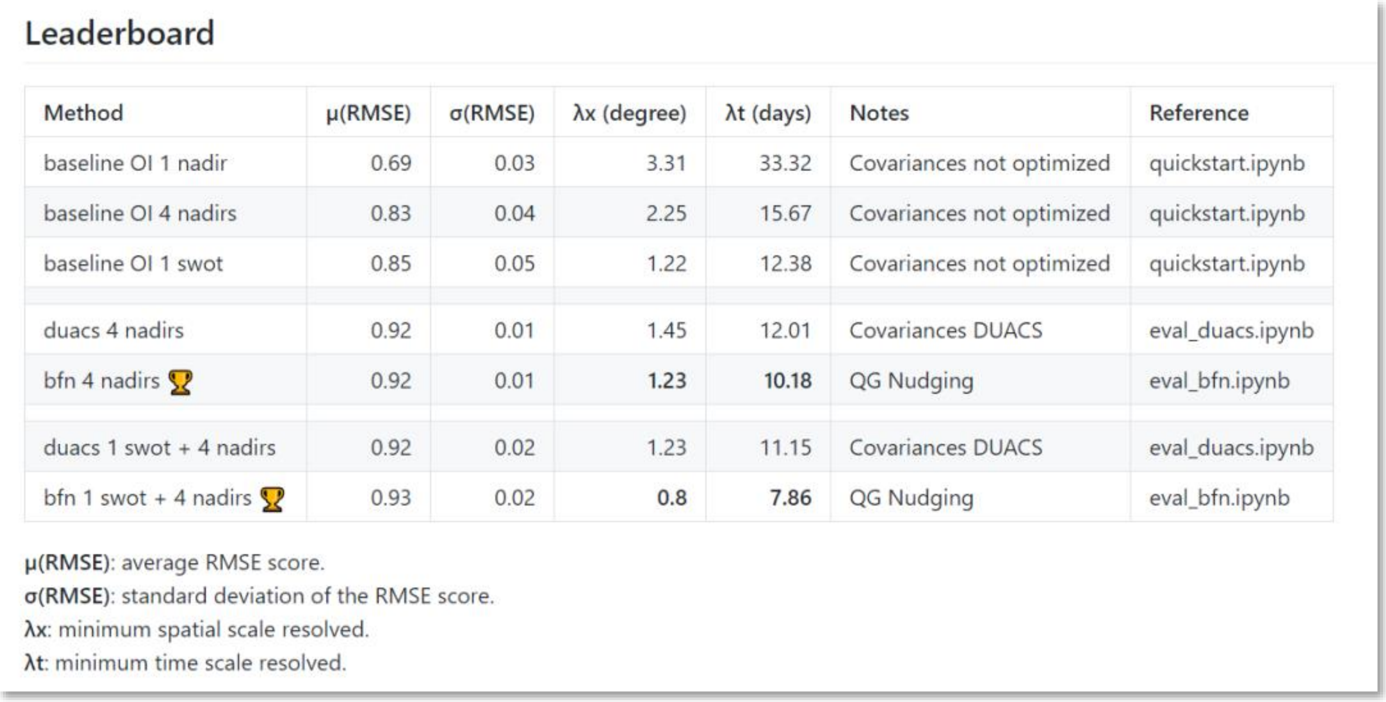
We hope that this open scientific work will be valuable for students and expert users, and that it will encourage and stimulate the ocean community to develop or participate in new challenges.

References

Ballarotta, M., Ubelmann, C., Pujol, M.-I., Taburet, G., Fournier, F., Legeais, J.-F., Faugère, Y., Delepoulle, A., Chelton, D., Dibarboure, G., and Picot, N.: On the resolutions of ocean altimetry maps, Ocean Sci., 15, 1091–1109, 2019.

Beauchamp, M. et *al.*: Intercomparison of Data-Driven and Learning-Based Interpolations of Along-Track Nadir and Wide-Swath SWOT Altimetry Observations. Remote Sens., 12, 3806, 2020.

Le Guillou, F. et *al.*: Mapping altimetry in the forthcoming SWOT era by back-and-forth nudging a one-layer quasi-geostrophic model, JTech, in press, 2020



Leaderboard

Method	μ(RMSE)	σ(RMSE)	λx (degree)	λt (days)	Notes	Reference
baseline OI 1 nadir	0.69	0.03	3.31	33.32	Covariances not optimized	quickstart.ipynb
baseline OI 4 nadirs	0.83	0.04	2.25	15.67	Covariances not optimized	quickstart.ipynb
baseline OI 1 swot	0.85	0.05	1.22	12.38	Covariances not optimized	quickstart.ipynb
duacs 4 nadirs	0.92	0.01	1.45	12.01	Covariances DUACS	eval_duacs.ipynb
bfn 4 nadirs 🏆	0.92	0.01	**1.23**	**10.18**	QG Nudging	eval_bfn.ipynb
duacs 1 swot + 4 nadirs	0.92	0.02	1.23	11.15	Covariances DUACS	eval_duacs.ipynb
bfn 1 swot + 4 nadirs 🏆	0.93	0.02	**0.8**	**7.86**	QG Nudging	eval_bfn.ipynb

μ(RMSE): average RMSE score.
σ(RMSE): standard deviation of the RMSE score.
λx: minimum spatial scale resolved.
λt: minimum time scale resolved.

Figure 2: Leaderboard available on the data-challenge repository, summarising the key scores for each method.

Reprocessing of a sea level L2P multi-mission dataset covering 28 years

C. Kocha[4], M. Lievin[2], B. Courcol[5], S. Philipps[2], I. Denis[1], T. Guinle[1], C. Nogueira loddo[3], G. Dibarboure[1], N. Picot[1], F. Bignalet Cazalet[1], A. Guerou[2] — [1] CNES, [2] CLS, [3] EUMETSAT, [4] CLS/CELAD, [5] CLS/ALTEN.

What is L2P?

A unified and up-to-date data set for all altimetry missions.

L2P products are netcdf homogeneous **along-track mono-mission products** that seek to provide the **same updated corrections and models for all processed missions** to facilitate inter-mission comparisons.

For each mission, the products contain (only on marine surfaces):

- The **sea level anomaly** (SLA);
- The **corrections** used to compute the SLA (range, orbital altitude, environmental and geophysical corrections) cleaned through empirical correction to remove errors in L2 products (e.g., time tag bias);
- **Selection of valid measurements** (validity flag), enabling users to discard data with spurious measurements;
- **Global and regional sea level biases** were corrected versus a reference mission to obtain consistent time series since the TOPEX/Poseidon mission.

Reprocessed L2P products are the inputs used by two Copernicus Services (CMEMS and C3S) to carry out their own reprocessing (L3 and L4 products) for assimilation experiments and climate monitoring.

L2P reprocessed in 2020

The whole altimetry L2P time-series was reprocessed in 2020; presented in Figure 1.

For each mission, the retracking parameters from L2 products (e.g. range) are kept, but each (geophysical and environmental) correction from L2 data used for sea level anomaly computation was evaluated and compared with other versions of the correction. Based on OSTST's recommendations for new standards and a thorough evaluation of all corrections, the best standards were selected to ensure the quality and consistency of this new version of L2P:

- The reprocessed L2P products were based on recently reprocessed L2 data for several missions: **ENVISAT V3.0, Sentinel-3 A & Sentinel-3 B Baseline Collection 004, SARAL GdrF, Cryosat Ocean Baseline C.**
- Use of **WGS84** Reference instead of Topex Ellipsoid.
- Available in **NetCDF-4** format.
- **New homogeneous, thoroughly assessed, updated corrections and models**, see Figure 2. (see Lievin et *al.* OSTST 2020).

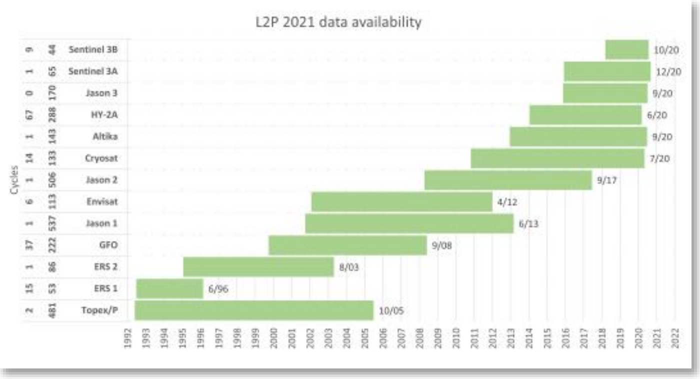


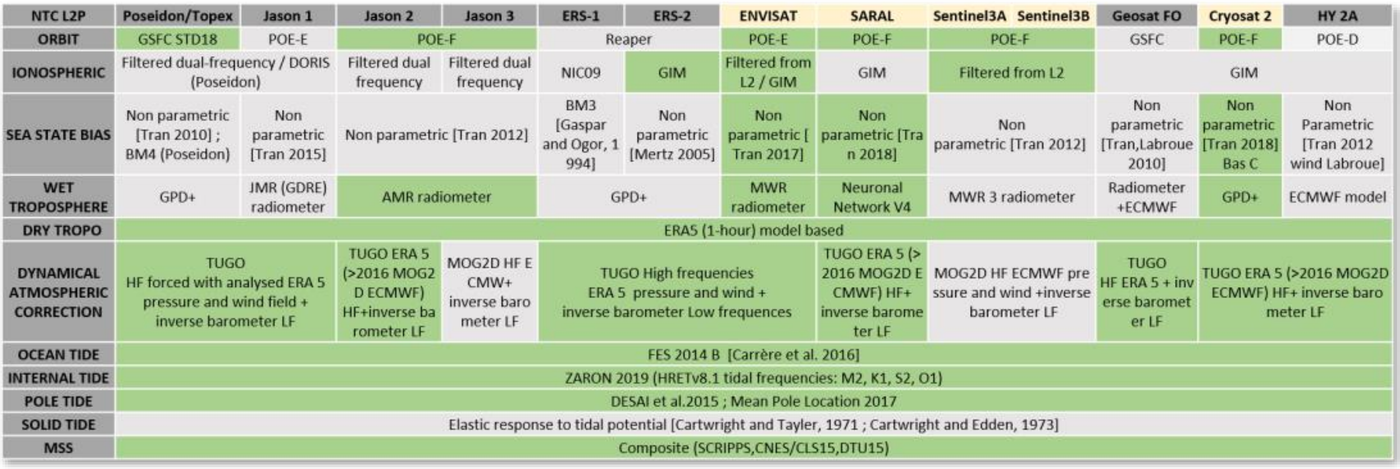
Figure 1. Missions reprocessed in standard L2P DT 2021. Credits: CLS, CNES, EUMETSAT.

Impacts of the reprocessing

The new corrections significantly contribute to reducing the sea surface height (SSH) error at crossover points. The error reduction for each mission is shown on Figure 3.

Some improvements are highlighted hereafter:

- The **new dynamic atmospheric correction** TUGO ERA5 solution accounts for more than 50% (~1 cm²) of the total improvements in SSH variance reduction in comparison with CCI products. Even for the most recent period, the improvement remains visible, showing the value of improved bathymetry and higher frequency forcing compared to operational (See Carrere et *al.* OSTST 2020).
- **Combined mean sea surface:** Using the advantages of each solution we observed improvements on SLA stability and studies over high latitudes were possible. MSS SCRIPPS is used in open ocean for its accuracy at



NTC L2P	Poseidon/Topex	Jason 1	Jason 2	Jason 3	ERS-1	ERS-2	ENVISAT	SARAL	Sentinel3A	Sentinel3B	Geosat FO	Cryosat 2	HY 2A
ORBIT	GSFC STD18	POE-E	POE-F		Reaper		POE-E	POE-F	POE-F		GSFC	POE-F	POE-D
IONOSPHERIC	Filtered dual-frequency / DORIS (Poseidon)		Filtered dual frequency	Filtered dual frequency	NIC09	GIM	Filtered from L2 / GIM	GIM	Filtered from L2		GIM		
SEA STATE BIAS	Non parametric [Tran 2010] ; BM4 (Poseidon)	Non parametric [Tran 2015]	Non parametric [Tran 2012]		BM3 [Gaspar and Ogor, 1994]	Non parametric [Mertz 2005]	Non parametric [Tran 2017]	Non parametric [Tran 2018]	Non parametric [Tran 2012]		Non parametric [Tran,Labroue 2010]	Non parametric [Tran 2018] Bas C	Non Parametric [Tran 2012 wind Labroue]
WET TROPOSPHERE	GPD+	JMR (GDRE) radiometer	AMR radiometer		GPD+		MWR radiometer	Neuronal Network V4	MWR 3 radiometer		Radiometer +ECMWF	GPD+	ECMWF model
DRY TROPO	ERA5 (1-hour) model based												
DYNAMICAL ATMOSPHERIC CORRECTION	TUGO HF forced with analysed ERA 5 pressure and wind field + inverse barometer LF		TUGO ERA 5 (>2016 MOG2D ECMWF) HF+inverse barometer LF	MOG2D HF ECMW+ inverse barometer LF	TUGO High frequencies ERA 5 pressure and wind + inverse barometer Low frequences			TUGO ERA 5 (>2016 MOG2D ECMWF) HF+ inverse barometer LF	MOG2D HF ECMWF pressure and wind +inverse barometer LF		TUGO HF ERA 5 + inverse barometer LF	TUGO ERA 5 (>2016 MOG2D ECMWF) HF+ inverse barometer LF	
OCEAN TIDE	FES 2014 B [Carrère et al. 2016]												
INTERNAL TIDE	ZARON 2019 (HRETv8.1 tidal frequencies: M2, K1, S2, O1)												
POLE TIDE	DESAI et al.2015 ; Mean Pole Location 2017												
SOLID TIDE	Elastic response to tidal potential [Cartwright and Tayler, 1971 ; Cartwright and Edden, 1973]												
MSS	Composite (SCRIPPS,CNES/CLS15,DTU15)												

Figure 2. Reference corrections overview (in grey: same standards as in the previous L2P version (L2P DT 2018), in green: standards updated in L2P reprocessed products (L2P DT 2021), in yellow: L2 reprocessed missions). Credits: CLS, CNES, EUMETSAT

short wavelengths, MSS CNES15 is used in coastal and some high-latitudes areas for its stability in coastal areas and MSS DTU15 is used in Arctic regions (latitudes > 81°N) for its spatial coverage.

- **New standard: Internal Tide** is included for the first time in L2P. The solution is from Zaron (2019) (HRET v8.1) using M2, S2, K1, O1 waves. Significant improvements were observed at mesoscales.

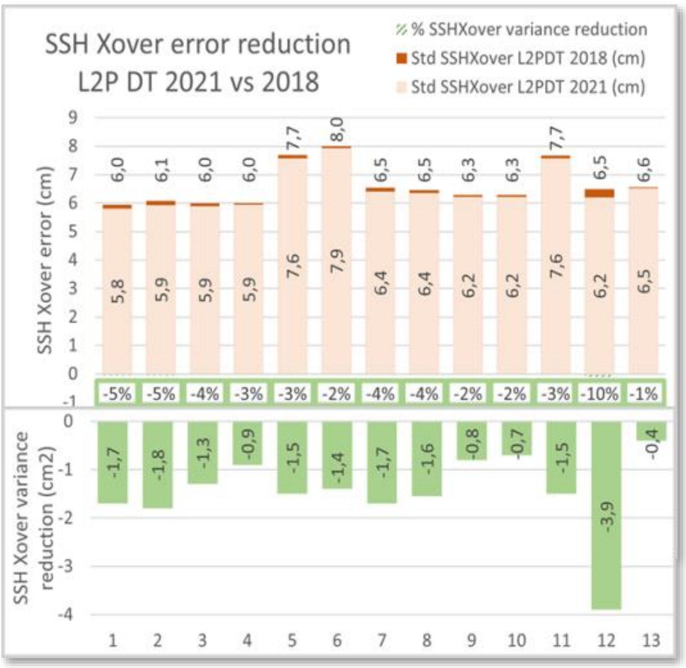


Figure 3. Sea surface height (SSH) error and variance reduction at crossover points for each mission. Credits: CLS, CNES, EUMETSAT.

The global mean sea level (GMSL)

The GMSL of reference missions has been recomputed with the new standard L2P 2021. The GMSL rise over the full altimetry era (~27 years) is estimated at **+3.45 mm/yr +/-0.4 mm/yr** (Figure 4) using the new standards for geophysical corrections, which is consistent with the trend derived from the previous L2P 2018 (+3.42 mm/yr with an uncertainty of 0.4 mm/yr @ 90% confidence level).

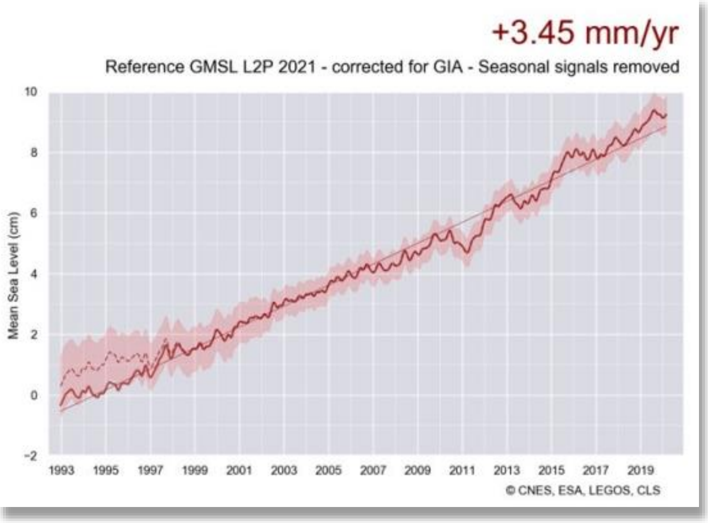


Figure 4. Reference GMSL time series (Topex-A/B; Jason-1; Jason-2 & Jason-3) computed with L2P 2021 products. The uncertainty (red envelope) of the GMSL measurements is based on a update of the GMSL error budget of Ablain et al. (2019). The corresponding uncertainty on the GMSL trend is +/-0.4 mm/yr over the 27 years. Credits CNES, ESA, LEGOS, CLS.

Download data

As part of the SALP project supported by CNES and of the Sentinel-3 Marine Altimetry L2P-L3 Service, L2P data (and user handbooks) are available to users for all the altimeter missions. They can be downloaded on the AVISO+ website.

Coming soon in L2P DT 2021: HY2B mission.

DOI to the dataset

Laurent Soudarin, CLS

This year, the AVISO+ service is starting to assign **Digital Object Identifiers** (DOI) to the datasets and products in its catalogue. The objectives of this change are to enable concise, accurate and reliable referencing as well as an estimation of the importance given to the datasets by users.

The first three DOIs were assigned to:

- the gridded sea-level heights in the Arctic Ocean,
- the altimetry data simulation along-track nadir and wide-swath altimeter SSH products performed with the SWOTsimulator,
- the climate indicators of ocean heat content and Earth energy imbalance.

More DOIs to come in 2021.

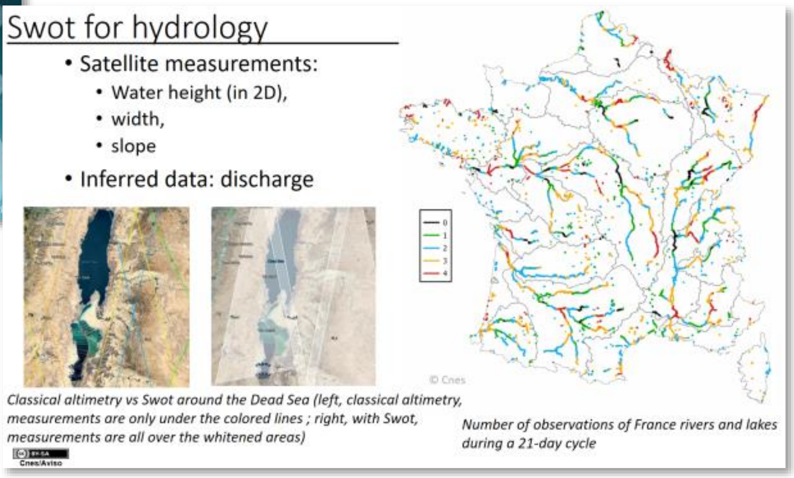
Series of slides on SWOT in hydrology


Swot in a nutshell

Find a series of pptx files presenting **hydrology from space and the Swot mission**.

They are splitted in six series of and are provided in English and in French and with a lighter version if need be (no illustrative images, no video embedded, images compressed).

Feel free to use them in your lectures and courses with the appropriate credits. Don't hesitate to send us your feedback.


Swot for hydrology

- Satellite measurements:
  - Water height (in 2D),
  - width,
  - slope
- Inferred data: discharge

Classical altimetry vs Swot around the Dead Sea (left, classical altimetry, measurements are only under the colored lines ; right, with Swot, measurements are all over the whitened areas)

Number of observations of France rivers and lakes during a 21-day cycle

Events

March 16-18, 2020 Saint-Malo, France, CFOSAT Science Team meeting

April 25-30, 2021 Vienna, Austria, EGU General Assembly

May 25-27, 2021 Virtual symposium, 2nd Operational Satellite Oceanography Symposium

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