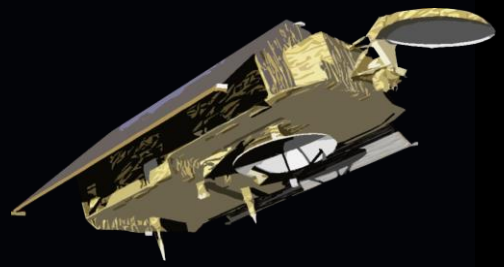


S6-JTEX
Inland Waters activities

Final Review

N. Taburet, T. Moreau, F. Boy, S. Amraoui

24/04/2024

Context – continental waters

➢ Operations

Sentinel-6MF data over inland waters are directly used in Copernicus Services both in STC in CGLMS and NTC in C3S as well as other operational services (e.g. Theia WL products on Hydroweb.Next)

Challenges are

- to ensure continuity wrt Jason-3 in the operational timeseries
- To meet precision requirements
- Being able to target new water bodies to expand the services

These services address lakes (CGLMS, C3S) and rivers (CGLMS) hence the study focused on these targets

➢ Other projects and activities

+ R&D activities through some CCI projects also use S6 data on these surfaces : **CCI Lakes** (ECV LWL), **CCI discharge** (ECV discharge)

+ Validation activities : S6 data are used for SWOT validation

+ Increasing need of EO data as input for the models and/or studies to tackle extreme events (droughts, floods…)

⇒ **All these projects need feedback on Sentinel-6MF data quality over inland waters**

Objectives and work plan

Objectives

- Valorisation of Sentinel-6 commissioning activities (CLS involved alongside Cnes)
- Validation of the S6-MF measurements over Inland Water
- Characterization of potential discrepancies and differences with respect to Jason-3
- Being able to target new water bodies under the historical Topex/Jason ground track thanks to the combination of Open Loop tracking mode and SAR acquisition mode allowing the innovative FFSAR processing technique

Tasks

- Task 1: **biases determination in between S6 and J3**
- Task 2: **Performances over inland waters**
- Task 3: **Performances of FF-SAR processing**

Deliverable = Article adressing S6 perfo over inland waters

Submitted to Remote Sensing end of 2023

1st review done, into 2nd round of review

remote sensing

MDPI

Article

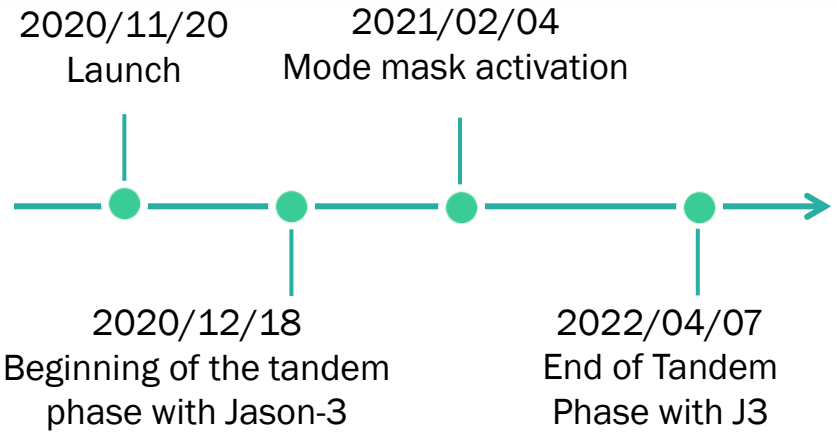
Characterization and exploitation of S6-MF products over in-land waters exploiting the tandem phase with Jason3, towards centimetric accuracy hydrology products.

Taburet Nicolas [1], Moreau Thomas [1], Amraoui Samira [1] and Boy François [2]

Methods and data

- Direct comparisons in between Jason3 and Sentinel-6MF data over the tandem phase December 2020 and April 2022
  - J3 : L2 Interim Geophysical Data Record from the processing baseline F
  - S6-MF : L2 Short time Critical (STC) PDAP

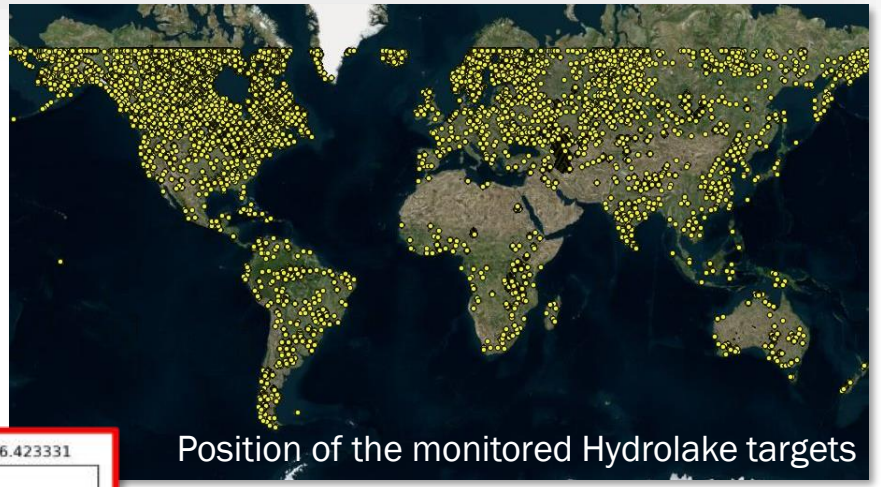
- comparisons to in-situ gauges to discuss the quality of J3 and S6 reconstructed water level timeseries over the tandem phase
  - To address performances of S6 PDAP products
  - To address the interest of other posting rates / other processings (Hamming, FFSAR)
  - Insitu data from French Schapi network (*https://hydro.eaufrance.fr/*).



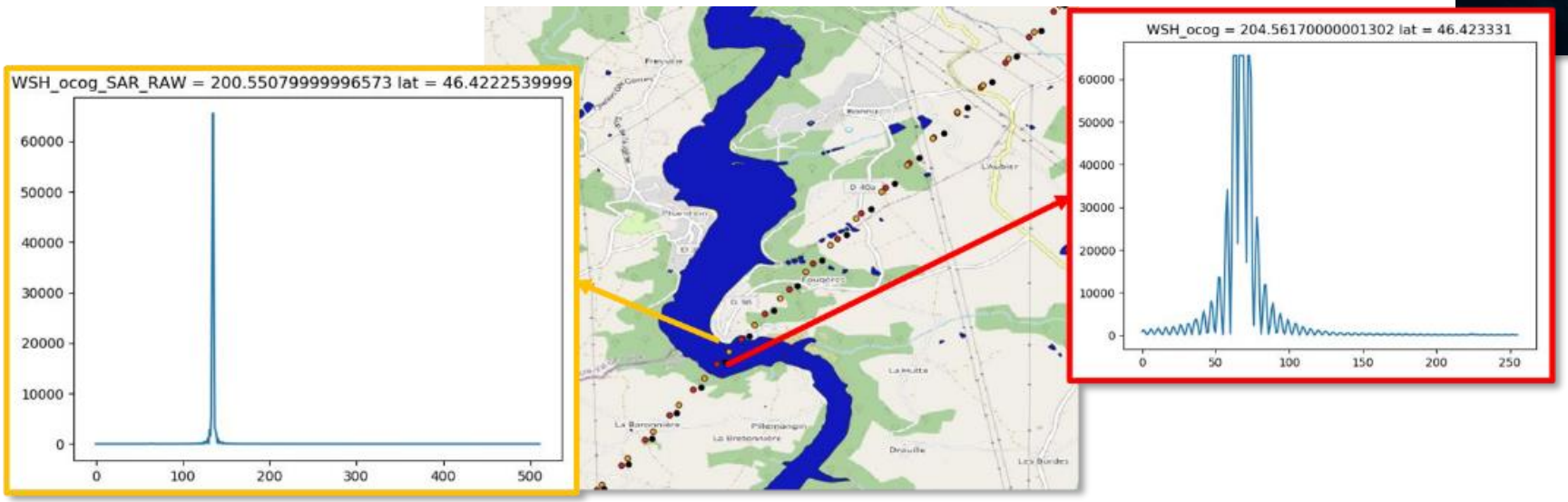
Task 1: biases determination in between S6 and J3

S6 LRM data vs J3

- comparing water level estimates from S6 LRM data over S6 cycles 13 to 24 with J3 data over the corresponding cycles (188 to 199) to quantify possible bias in between both estimates.
- Comparisons performed over data extracted at the nadir of lakes from the Hydrolake database
- More than 1 million colocated points (20Hz data)



Position of the monitored Hydrolake targets



Cycle 10 over France. LX mode. Eguzon reservoir
Red = S6A LRM / Orange = S6A SAR

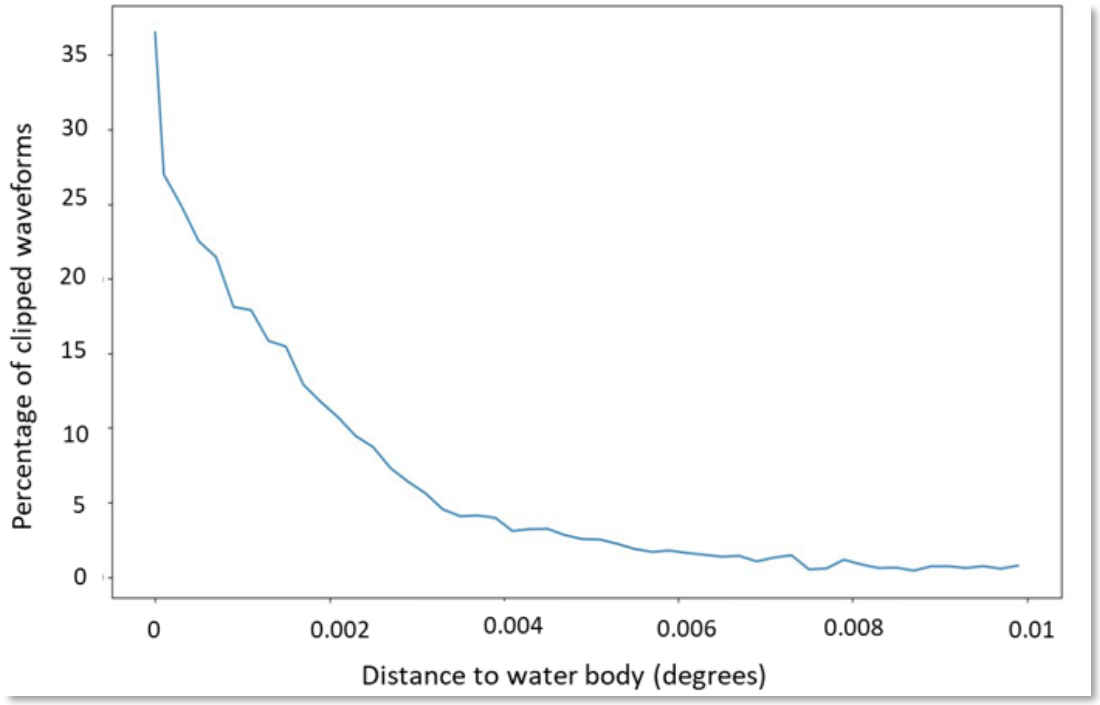
Clipped waveform
⇨ **range underestimated** and WSH overestimated with OCOG retracker
⇨ by ~4 meters in this example

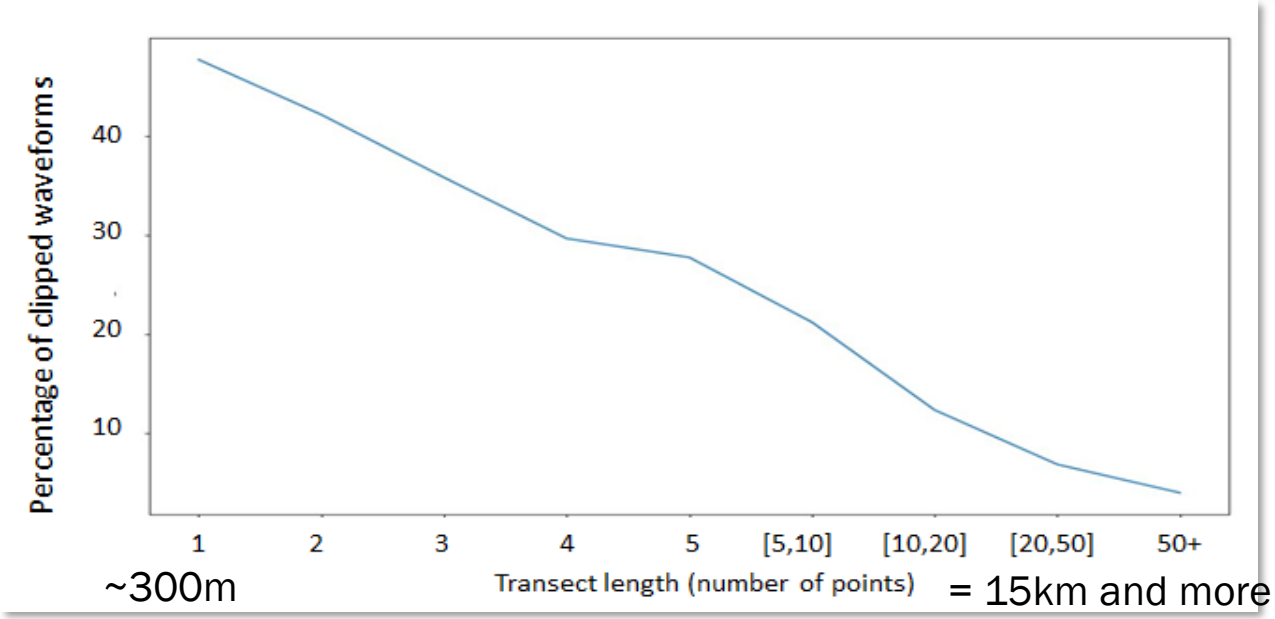
Nb: some studies show clipping impact can be mitigated on peaky waveforms by using specific retrackers fitting the secondary lobes (e.g. sinc² retracker CNES/Hydromatters)

Task 1: biases determination in between S6 and J3

S6 LRM data vs J3

Lakes : On average 13% of the waveforms at water nadir present clipping but the distribution strongly depends on targets size (which is closely linked to surface roughness): from 45% over small targets (which are thus often smooth and highly reflective, resulting in return signals of high amplitude) to 5% over larger ones





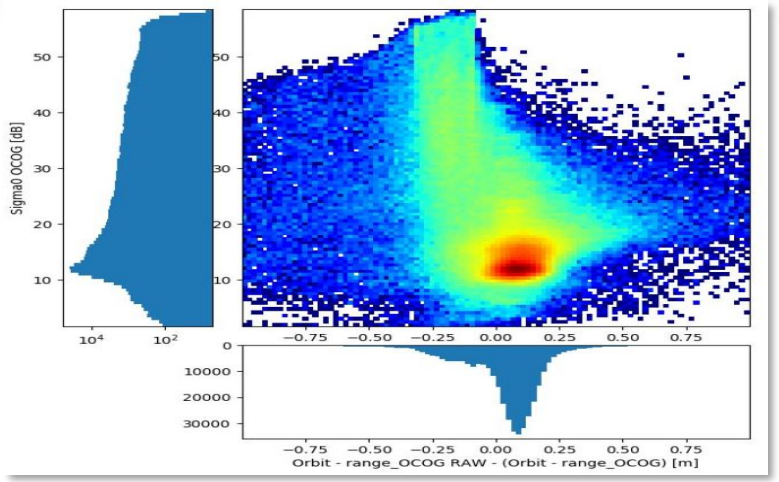
Rivers : Confirmed at the nadir of rivers (Carthage database, cycles 10 to 24 over France):
The percentage of clipped waveforms for points up to 1km of nadir to the water bodies was computed.
Clipping percentage quickly decreases with distance to water bodies from 36.5 to 5% for distances ranging from 0 to 300m

Task 1: biases determination in between S6 and J3

S6 SAR vs S6 LRM bias (OCOG retracker)

Colocalisation of S6 LRM and S6 SAR raw data, within Hydrolakes polygons (cycles 13 to 24)

Sigma0 OCOG presents 2 populations : one around 12dB associated to long transects over ocean like targets. Another with high sigma0 values (> 20dB) reflects the distribution obtained over DB Carthage small targets.



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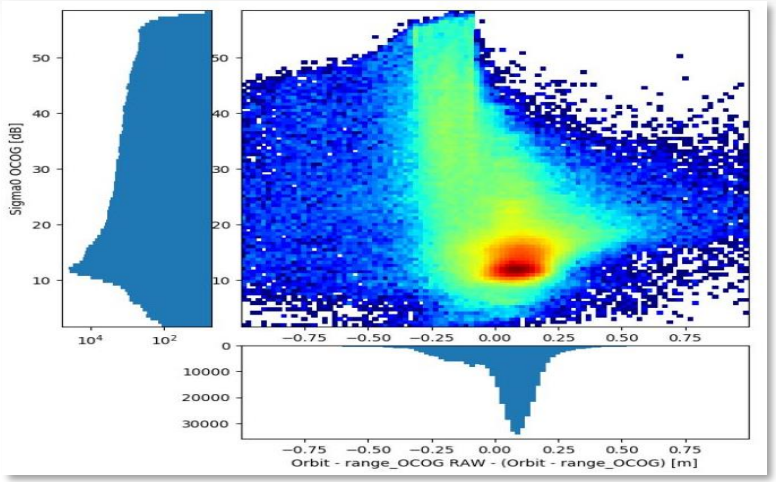
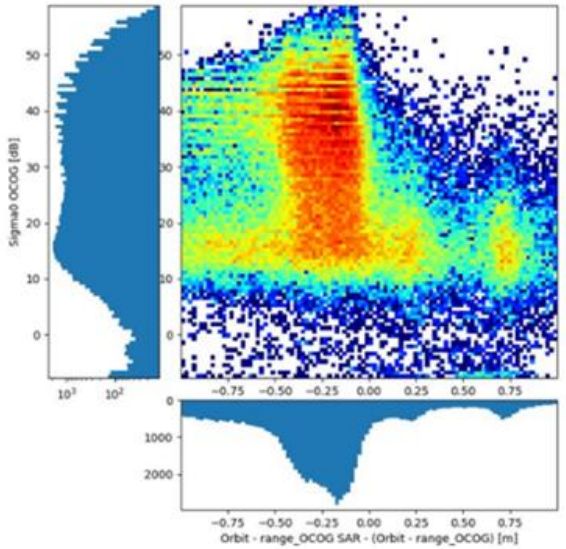
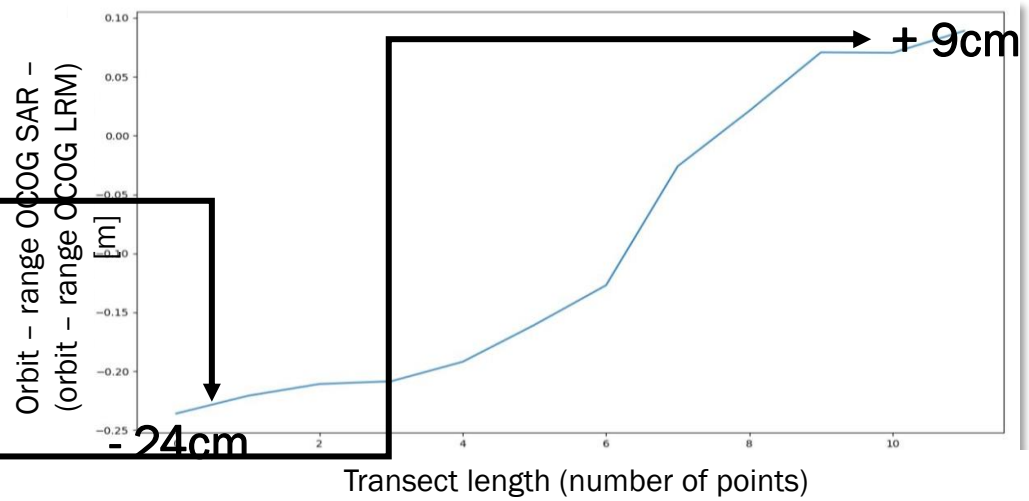




Small transects, High sigma0, small water bodies, more than 20 cm negative bias

Large targets, Low sigma0, large water bodies, few cm positive bias



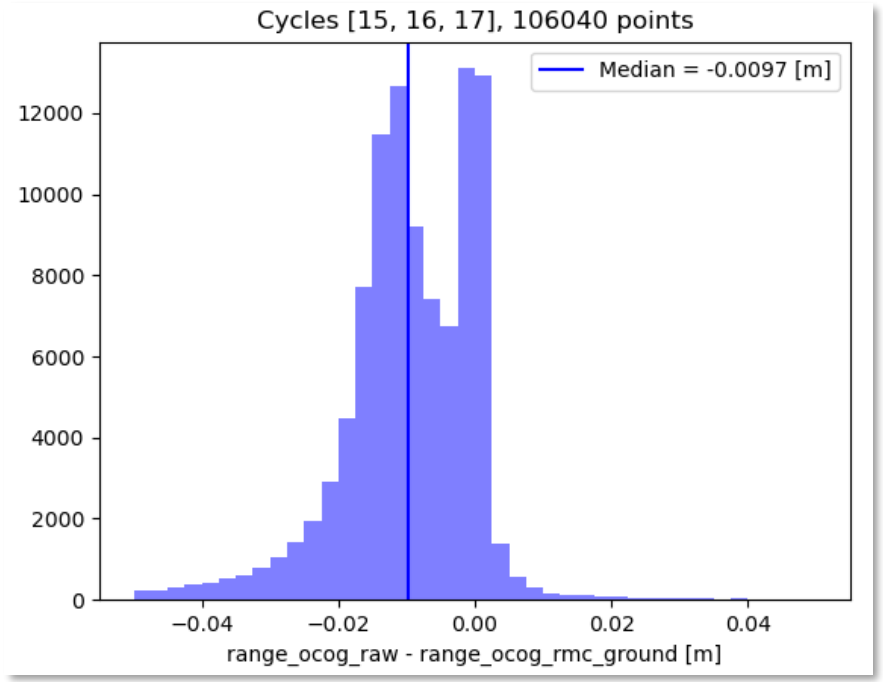
Task 1: biases determination in between S6 and J3

S6 SAR RMC vs S6 SAR RAW (OCOG retracker)

The SAR RMC used for this comparison is that reconstructed on the ground from the SAR RAW transmitted waveforms, with similar processing as what is performed onboard for the RMC compression

Median difference ~1cm

- Differences can be explained by the truncated waveforms in SAR RMC which affects the WF normalisation and hence the peak detection by OCOG algorithm.
- In some rare cases, the truncated waveforms in SAR RMC prevent the detection of a peak seen in SAR RAW when located in a gate number > 263.
- The **RAW / RMC GROUND range values are consistent** to 5cm in 87% of the cases, **96% when considering sigma0 > 12 dB** provided that the waveform is correctly centred in the first half of the tracking window
- Percentage of differences larger than 1 and 10m are of 2.5 and 1.1% respectively for sigma0 > 12dB. In 90% of the cases, these differences are attributed to the positioning of the retracked peak in RAW waveforms in gates not accessible in RMC. This can be fixed by correcting the OLTC to bring back the peak within lower gates numbers



Distribution of the differences in between the range derived from the RAW and RMC waveforms with OCOG retracker

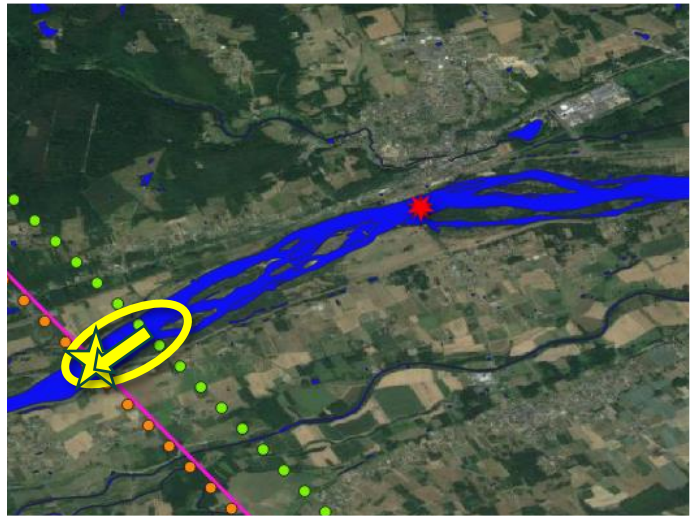
Task 2: Performances over inland waters

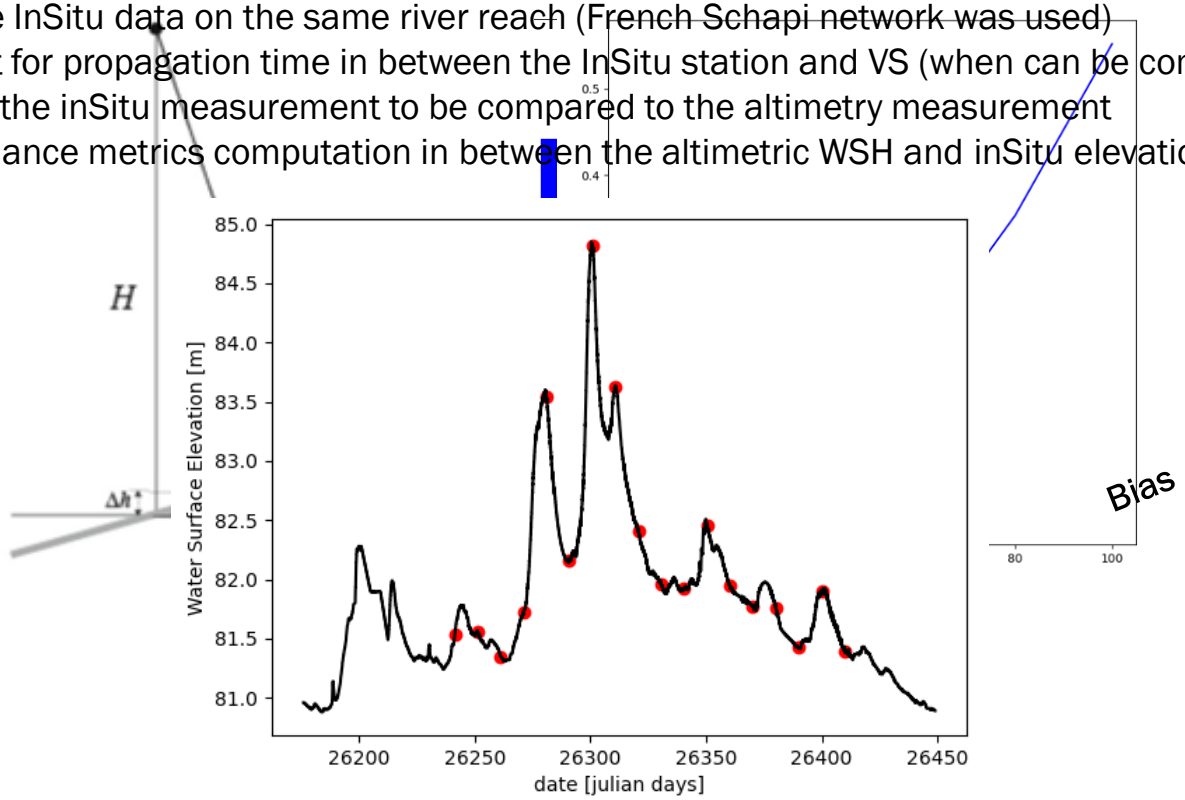
Validation with respect to inSitu measurements

Method (developed within St3tart project)

Water level timeseries were reconstructed over several satellite/river crossings defining Virtual Stations (VS). Accounting for:

- Water Surface Mask (selection within or closest to)
- Correct for the elevation difference induced by the river slope to “relocate” all points at the station centre
- Account for POCA displacement (slope induced)
- Retrieve InSitu data on the same river reach (French Schapi network was used)
- Account for propagation time in between the InSitu station and VS (when can be computed) to select the inSitu measurement to be compared to the altimetry measurement
- Performance metrics computation in between the altimetric WSH and inSitu elevation series





$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - y_i)^2}$$

U-RMSE

Correlation

% of valid data

Task 2: Performances over inland waters

Validation with respect to inSitu measurements

- 3 classes of stations:
- Class 1: **flat** canals.
- Class 2: rivers presenting a **slope**. (=> slope residuals induce additional uncertainty in the reconstructed timeseries)
- Class 3: rivers presenting important **meandering** or/and surrounded by one or several **other water bodies, acting as contaminants**. (add signature in altimetric waveform, can induce retracking errors)

Class 2. 12 sites. Performances independant of river width. Precision is of

- 9.7 cm for S6A SAR
- 29.0 cm for J3

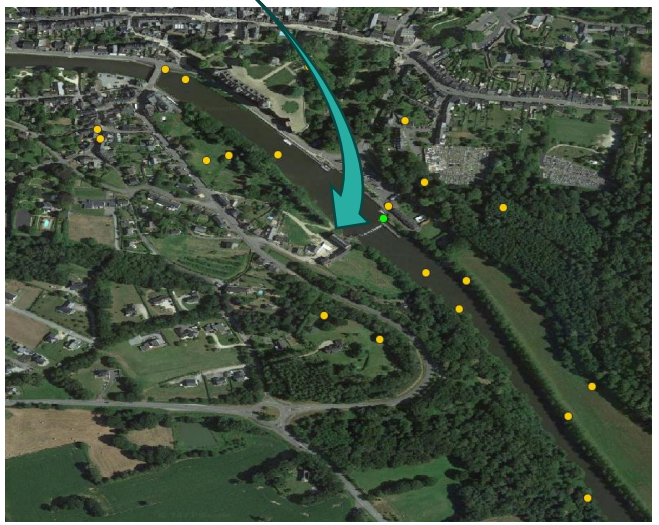
Class 3. 22 sites. The median value of u-RMSE, for the VS where correlation is higher than 0.6, is

- 22.6cm for S6 PDAP
- 30.2cm for J3

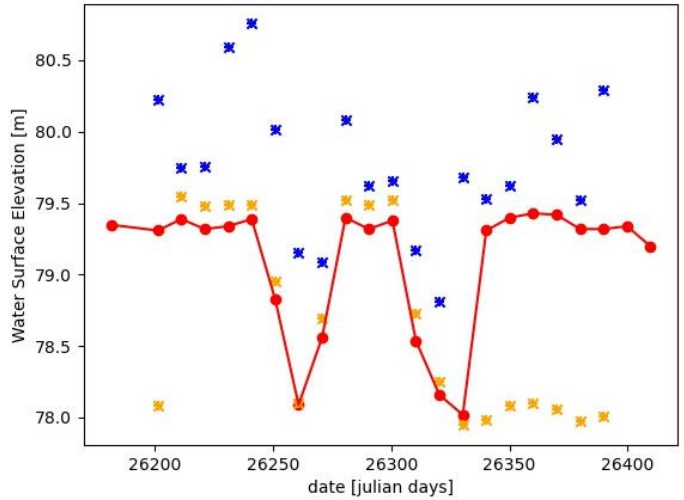
Name	Mission/product/Retracker	Pearson coeff	RMSE [m]	Bias [m]	U-RMSE [m]	Nb. of cycles	Nb of points within 2m of the in-situ
Somme Canal	S6/PDAP 20Hz/OCOG	0.970	0.143	0.141	0.023	10	10
	J3/20Hz/Ice1	0.661	0.364	0.323	0.167	10	10

Class 1 **Ideal case** :

- **S6 SAR 2.3 cm u-rmse**, 14cm bias
- **J3 16.7 cm u-rmse** 32cm bias (OCOG retracker)



Green = in situ station position, yellow = position of the nadir of successive cycles altimetry data



red = in situ time series, blue = J3 timeseries, yellow = S6A SAR timeseries

Task 2: Performances over inland waters

Validation with respect to inSitu measurements

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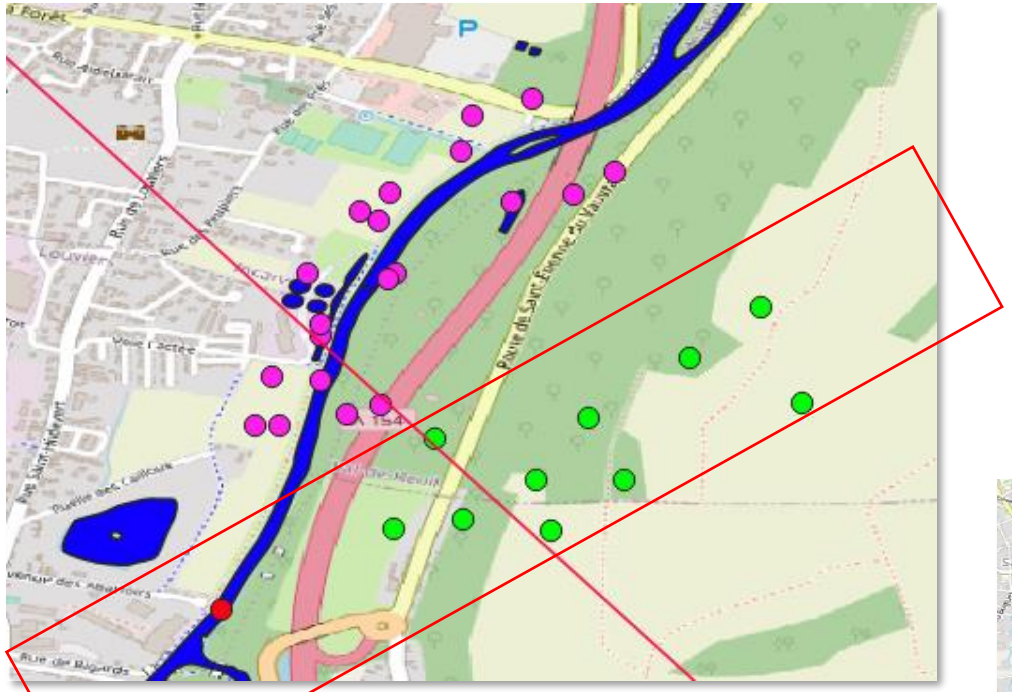
Name	In Situ	Mission/product/Re-tracker	Pearson coeff	RMSE [m]	Bias [m]	U-RMSE [m]	Nb. of cycles	Nb of points within 2m of the in-situ
Loire Langeais	K683002001	S6/PDAP 20Hz/OCOG	1.000	0.050	-0.022	0.045	16	16
		J3/20Hz/Ice1	0.973	0.412	0.347	0.222	16	16
Rhone in Ternay	V303002002	S6/PDAP 20Hz/OCOG	0.987	0.163	-0.155	0.050	8	8
		J3/20Hz/Ice1	0.429	0.532	0.350	0.401	8	8
Garonne in La Réole	O919001991	S6/PDAP 20Hz/OCOG	0.998	N/A**	N/A	0.102	20	20
		J3/20Hz/Ice1	0.957	N/A	N/A	0.439	20	19
Garonne in Marmande	O909001001	S6/PDAP 20Hz/OCOG	0.999	N/A	N/A	0.092	19	19
		J3/20Hz/Ice1	0.994	N/A	N/A	0.281	19	19
Garonne in Marmande2	O909001001	S6/PDAP 20Hz/OCOG	0.996	N/A	N/A	0.212	19	19
		J3/20Hz/Ice1	0.991	N/A	N/A	0.322	19	19

Name	In Situ	Mission/product/Re-tracker	Pearson coeff	RMSE [m]	Bias [m]	U-RMSE [m]	Nb. of cycles	Nb of points within 2m of the in-situ
Herault in StGuilhem	Y214002001	S6/PDAP 20Hz/OCOG	0.875	N/A	N/A	0.936	10	9
		J3/20Hz/Ice1	0.464	N/A	N/A	0.664	10	7
Gimone in Gimont	O274331001	S6/PDAP 20Hz/OCOG	0.829	N/A	N/A	0.255	19	12
		J3/20Hz/Ice1	0.533	N/A	N/A	1.014	19	11
Adour in Onard	Q142001001	S6/PDAP 20Hz/OCOG	0.994	N/A	N/A	0.200	4	3
		J3/20Hz/Ice1	0.999	N/A	N/A	0.290	4	3
Dropt in Loubens (pass 35)	O937251002	S6/PDAP 20Hz/OCOG	0.846	N/A	N/A	0.787	16	16
		J3/20Hz/Ice1	0.756	N/A	N/A	0.777	16	13
Dadou in Montdragon	O477401001	S6/PDAP 20Hz/OCOG	0.746	N/A	N/A	0.252	16	16
		J3/20Hz/Ice1	0.593	N/A	N/A	0.290	16	16
Loire in Villerest	K091001010	S6/PDAP 20Hz/OCOG	0.955	0.297	0.275	0.114	13	12
		J3/20Hz/Ice1	0.738	1.018	0.968	0.315	13	13
Vezouze in Thiébau-ménil	A654111001	S6/PDAP 20Hz/OCOG	0.387	0.985	0.819	0.548	11	11
		J3/20Hz/Ice1	0.628	1.037	0.923	0.474	11	5
Vègre in Asnière sur Vègre	M058302010	S6/PDAP 20Hz/OCOG	N/A	N/A	N/A	N/A	9	0
		J3/20Hz/Ice1	N/A	N/A	N/A	N/A	9	0

Task 2: Performances over inland waters

Validation with respect to inSitu measurements - A new definition of Virtual Stations

Considering all these difficulties induced by river slope, meanders, steps and surrounding contaminants, it is worth **defining virtual stations at a more opportunistic location** where these **elements impacts can be mitigated**

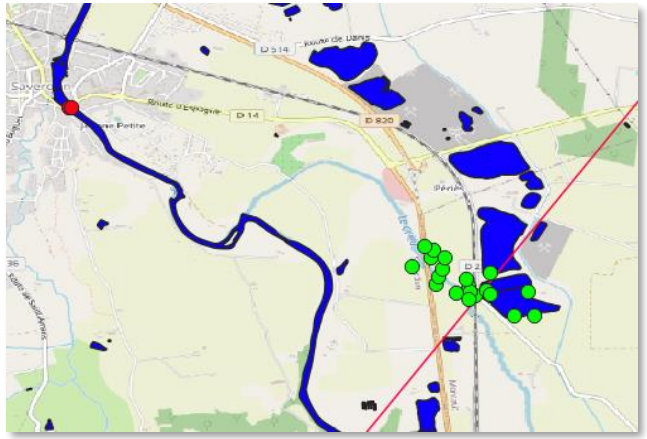


Red dot = in situ station position, Red rectangle = SAR band intersecting insitu position

Exploit the SAR band footprint
- select data off nadir of the river
- all these SAR bands **probe the same section of the river**
- **correct for slant range elongation**

➢ Direct comparison of water level timeseries at the insitu position
= no need for slope, poca correction in the altimetric timeseries
= no need to account for flow propagation time in between VS and inSitu station

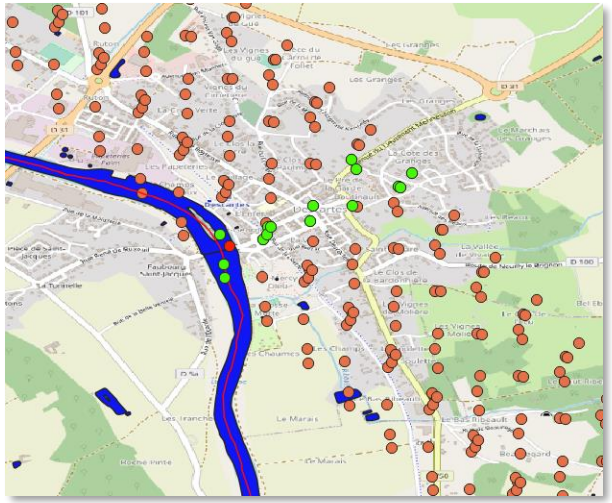
➢ **precision strongly improves for the Eure River from 12 cm to 3.4 cm u-RMSE** as the off-nadir VS definition allows to avoid contamination



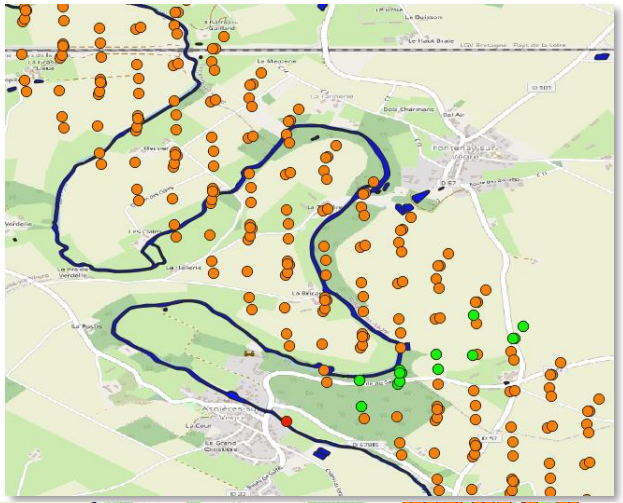
➢ This does not work everywhere:
Example of unfavorable configuration for off nadir VS definition

Task 2: Performances over inland waters

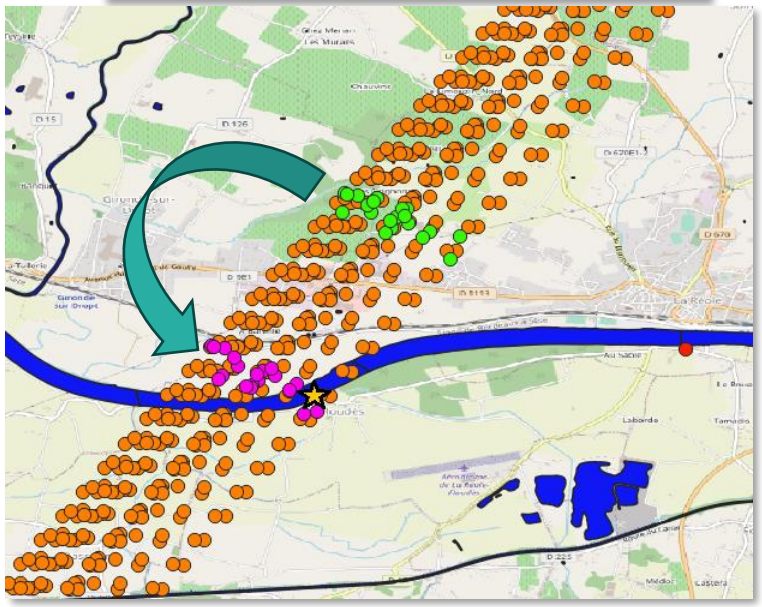
- Altimetric **VS** can now be **defined** in new situations **where it was not previously possible**



- The theoretical ground track does not cross the River.



- The theoretical ground track samples too many portions of the river



- **Or shift the comparison to a 'cleaner' portion of the river**

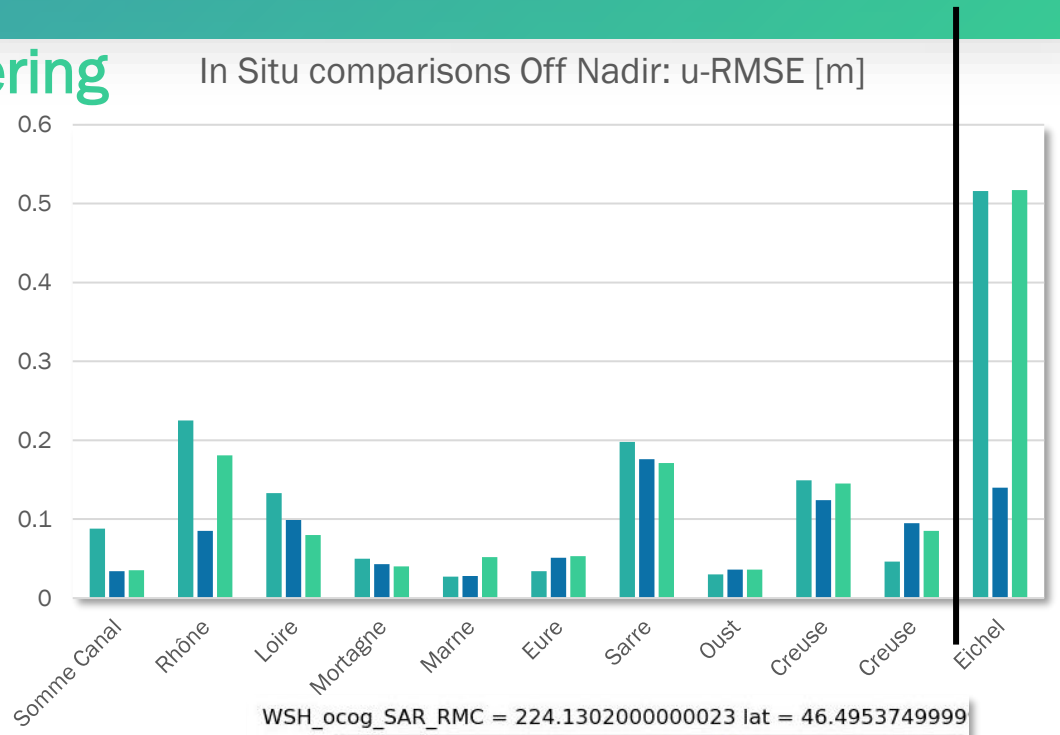
  Such definition was shown to improve the precision of water level timeseries up to 3 to 4 cm u-RMSE in some favourable cases when waveforms are not contaminated by other close waterbodies or meanders lying in the SAR band.

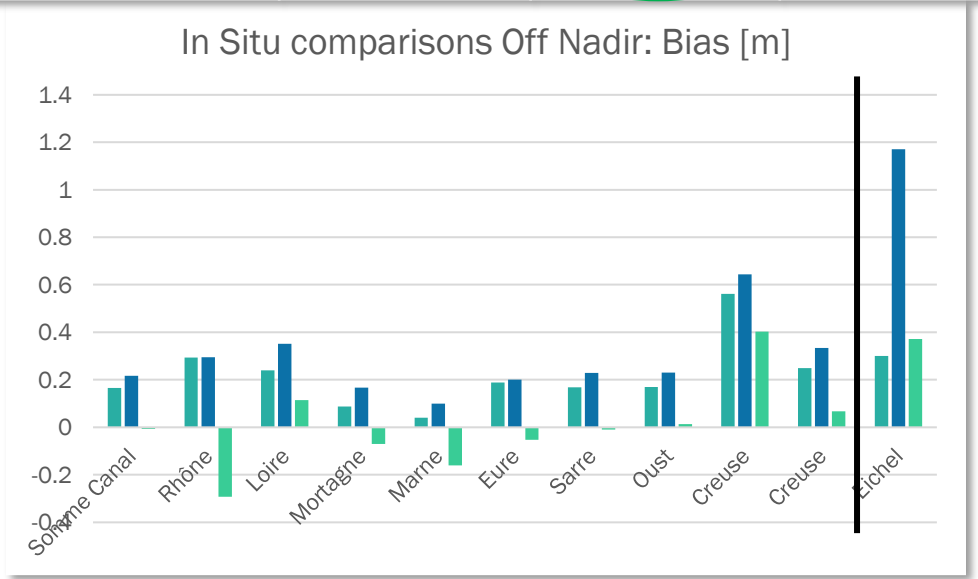
Task 2: Performances over inland waters

Validation with respect to inSitu measurements – Hamming filtering

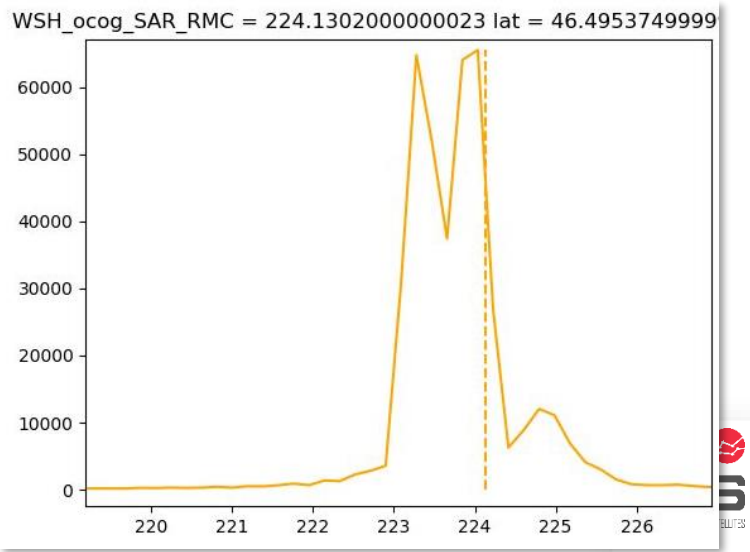
- SMAP processor used to reprocess S6-MF L1B and L2 products
- Processing includes **Hamming filtering** => only signal coming from the SAR band remains
- 12 stations considered, very good performances over the first 10.

	U-RMSE	Bias	% valid data
PDAP OCOG	9.8 cm	21.6 cm	85%
SMAP OCOG (Hamming)	7.7 cm	27.7 cm	90%
SMAP SINC² (Hamming)	8.7 cm	0.002 cm	95%





- 2 stations present bad performance : Eichel and Vègre (no valid data on this one) due to contamination (wrong peak is retracked)

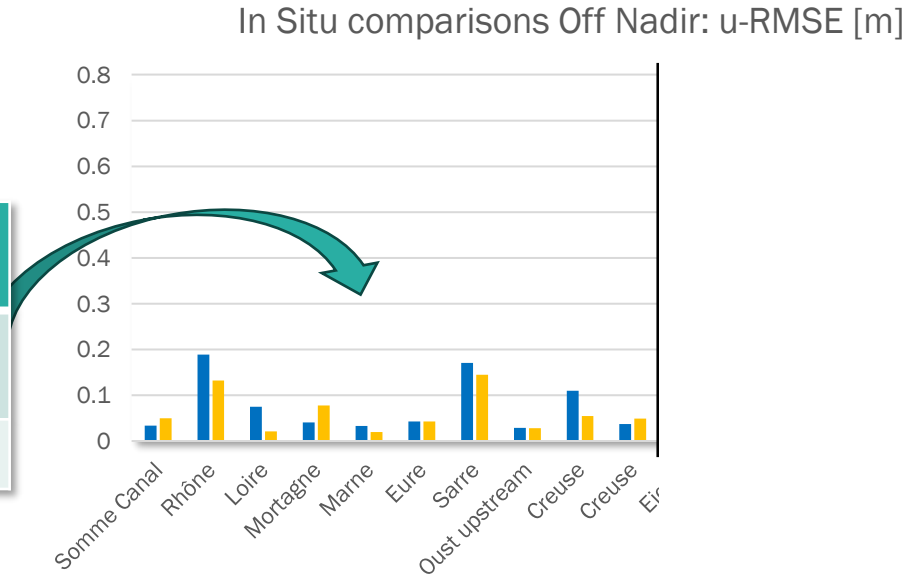


Task 3: FFSAR processing

Validation with respect to inSitu measurements – Fully Focus SAR

- All the pulses returning from a same target are processed => further increases the along-track resolution with respect to UFSAR
- 18 stations considered:
  - 10 simple configurations : slight 18% precision improvement

	Mean U-RMSE	Mean Bias	% valid data
SMAP (140Hz) SINC² (Hamming)	7.6 cm	1.1 cm	93%
SMAP FFSAR (140Hz) SINC²	6.2 cm	-4.8 cm	94%



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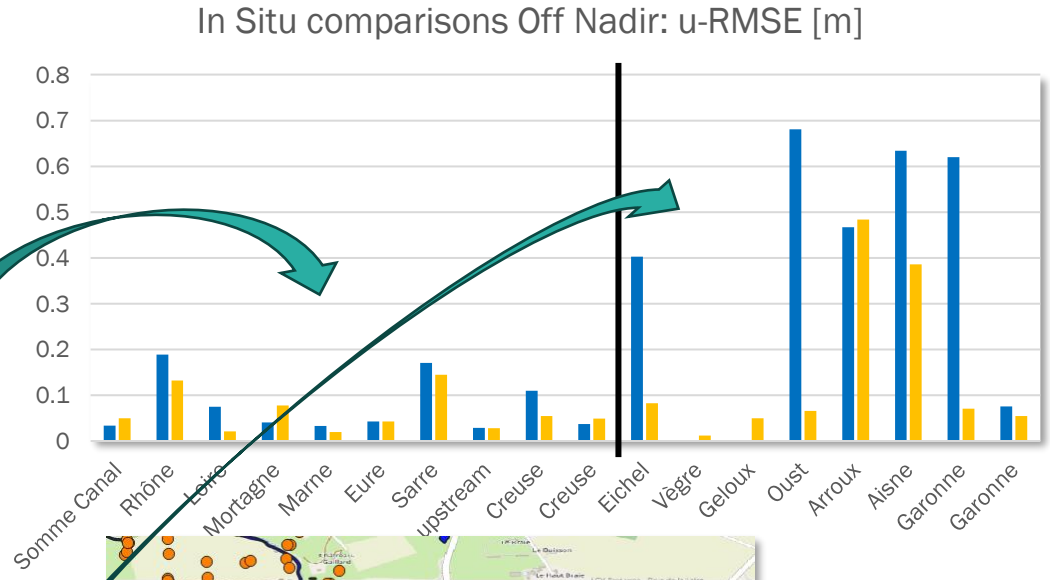
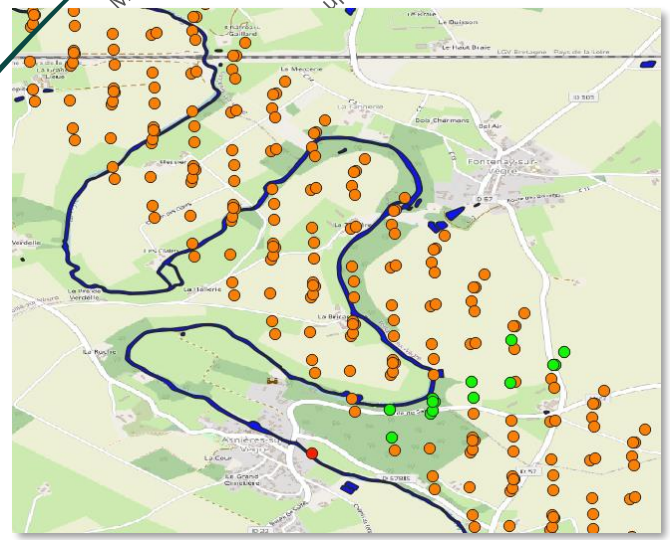
  - +8 complex cases: FFSAR brings significant precision improvement

	Mean U-RMSE	Mean Bias	% valid data
SMAP (140Hz) SINC² (Hamming)	22.8 cm	3.1 cm	83%
SMAP FFSAR (140Hz) SINC²	10.2 cm	-0.001 cm	90%





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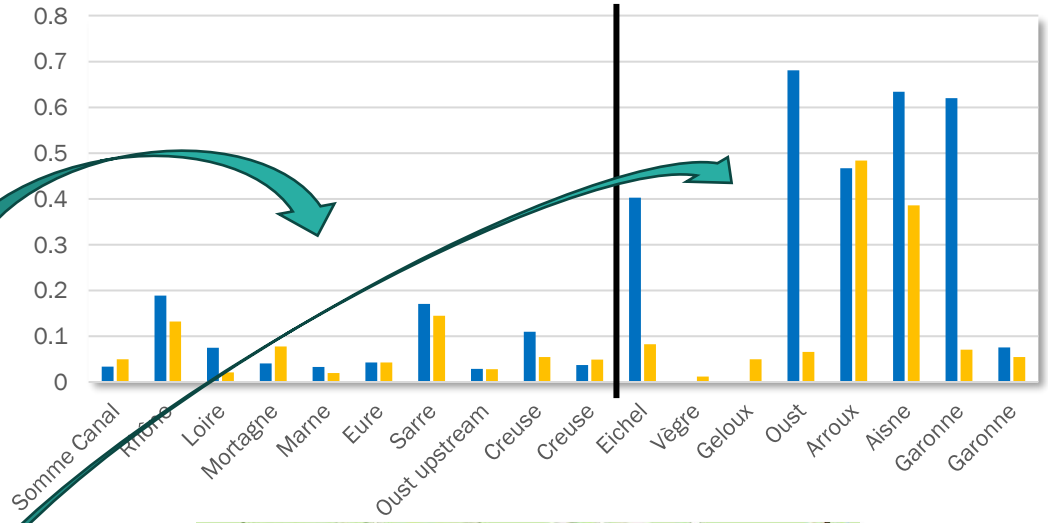
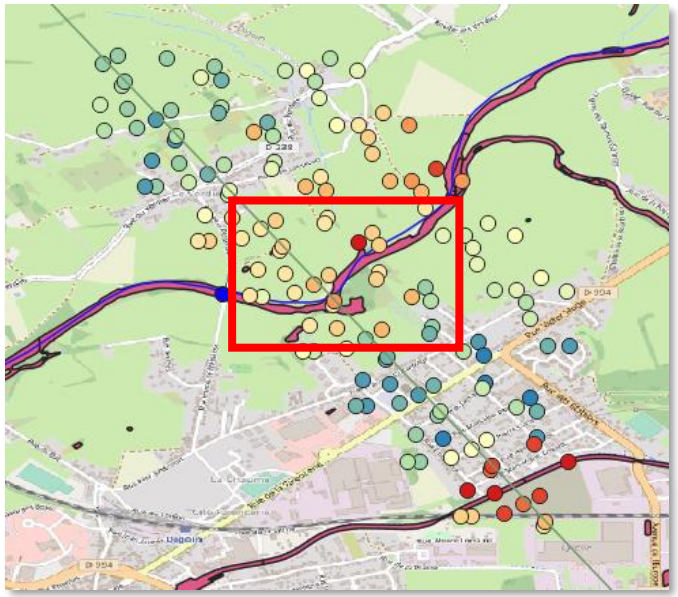
  - +8 complex cases: FFSAR brings significant precision improvement

	Mean U-RMSE	Mean Bias	% valid data
SMAP (140Hz) SINC² (Hamming)	22.8 cm	3.1 cm	83%
SMAP FFSAR (140Hz) SINC²	10.2 cm	-0.001 cm	90%

In Situ comparisons Off Nadir: u-RMSE [m]





- Very complex cases (Aisne: the in-situ gauge is situated at a lock position, Arroux: meanders and confluence very close to the gauge position…) cannot be reconstructed with precisions better than 40cm

=> Need for dedicated retrackers selecting the correct peak (Cnes LPP + CLS has started some studies with Cnes over rivers)

Conclusions & Roadmap

- Important **clipping in S6 LRM** waveforms => exploit SAR over land
- Tandem phase allowed the **qualification of the SAR / LRM bias which is sigma0 dependant (OCOG retracker).** Of interest to reconstruct unbiased timeseries over the Jason-S6 period

=> Accounted for in Copernicus Land Monitoring and C3S for example

- S6 confirms benefits of SAR over LRM in terms of **precision. 3 cm** is attained at nadir over simple cases
- **SAR allows defining a new type of virtual stations: Off-Nadir VS**

=> **very useful for absolute bias quantification** wrt insitu comparisons to **avoid slope and lag time difficulties**

=> **Sinc² retracker almost unbiased** (compared to OCOG with about 20cm bias)

- **Complex cases** (meanders, locks/steps) are **better handled** with **Hamming filtering and even further with FFSAR : better than 10 cm precision can be achieved**

➢ **Very complex cases** cannot be reconstructed with precisions better than 40cm => See the roadmap for proposed directions for dedicated retrackers targeting several peaks or subsections in the waveforms

Conclusions & Roadmap

Roadmap

- **Importance of long enough tandem phases** (several cycles) **for hydro CalVal** to have enough points of comparisons with in-situ as well as downstream application to be able to compute intermission biases
- Continue R&D to **exploit off nadir signal**
- Develop **multi peak retracking algorithms and/or focus on a section of the waveform** to handle contamination by other water body echoes (Cnes LPP + CLS has started some studies with Cnes over rivers)
- To fully exploit S6-MF improved performances wrt J3, river slope must be accounted for (also shown by other projects e.g. St3tart)
  - IceSat2 & SWOT provide such information
  - In combination with the second S6-MF / J3 tandem phase this method should allow to emphasize that S6-MF improved performances can now be exploited over rivers with significant slope (>30cm/km) to reconstruct WL timeseries better than J3 ones.
- Exploiting the potential of the newly introduced **'off nadir' virtual stations presented in the study should be pushed further.** In particular to address VS at distances larger than 1 or 2 km our first study was limited to. With larger slant ranges corrections to be applied, the **sensitivity of the reconstructed Water Level estimates to the correct identification of the backscattering surface** increases. **Combined analysis of the Sentinel-6MF SAR radargrams with SWOT maps of the backscatter coefficient** should be performed to better understand and exploit the off nadir S6-MF radargrams.
- Synergies to do with LIT activities to enlight S6 performances over high latitude inland waters