St3TART
FRM for Sentinel-3 Land Altimetry

Sentinel-3 Topography mission Assessment through Reference Techniques (St3TART)

FRM Campaign final report for inland waters

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2	1	17/04/2023	Integration of ESA RIDs

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2	1	M	30, 60, 86, 96	Minor changes to integrate ESA RIDs

* *I = Inserted* *D = Deleted* *M = Modified*

Acronyms

The acronyms used in this document are defined in [RD5].

Reference documents

N°	Reference	Title
[RD1]	ESA-EOPG-CSCOP-SOW-29, Issue 1 Rev. 4 – 28/10/2020	Statement of Work - Sentinel-3 Topography mission Assessment through Reference Techniques (St3TART)
[RD2]	NOV-FE-0899-PR-002	Technical Proposal
[RD3]	NOV-FE-0899-PR-004	Implementation Proposal
[RD4]	ESA Contract No. 4000135181/21/I-DT	ESA Contract – Copernicus ground segment Sentinel-3 Topography mission Assessment through Reference Techniques (St3TART)
[RD5]	NOV-FE-0899-NT-040	Acronyms list
[RD6]	NOV-FE-0899-NT-050	TD-6: Roadmap for S3 STM inland water FRM operational provision
[RD7]	NOV-FE-0899-NT-055	TD-11-1: FRM Campaign Technical Handbook for S3 STM Inland Water Products
[RD8]	NOV-FE-0899-NT-042	TD-1: FRM Protocols and Procedure for S3 STM Inland Water Products
[RD9]	NOV-FE-0899-NT-076	TD-12: FRM Campaign log: Drone campaign in Marmande (Garonne River)
[RD10]	NOV-FE-0899-NT-077	TD-12: FRM Campaign log: Installation of vorteX.io Micro-Stations in Marmande
[RD11]	NOV-FE-0899-NT-079	TD-12: FRM Campaign log: Installation of vorteX.io Micro-Stations near Strasbourg
[RD12]	NOV-FE-0899-NT-078	TD-12: FRM Campaign log: Installation of vorteX.io Micro-Stations over the Po River
[RD13]	NOV-FE-0899-NT-084	TD-12: FRM Campaign log: Installation of vorteX.io Micro-Stations in Trèbes
[RD14]	NOV-FE-0899-NT-089	TD-12: FRM Campaign log: Installation of vorteX.io Micro-Stations in Marmande (2nd phase)
[RD15]	NOV-FE-0899-NT-090	TD-12: FRM Campaign log: 2nd Drone campaign in Marmande (Garonne River)
[RD16]	NOV-FE-0899-NT-108	TD-12 FRM Campaign logs: Installation of vorteX.io Micro-Stations in Alsace
[RD17]	NOV-FE-0899-NT-114	TD-12 FRM Campaign logs: Installation of vorteX.io Micro-Stations over the Tiber River

[RD18]	NOV-FE-0899-NT-116	TD-12 FRM Campaign logs: Installation of vorteX.io Micro-Stations over the German part of the Rhine River
[RD19]	NOV-FE-0899-NT-107	TD-12: FRM Campaign log: Drone campaign in Alsace (Rhine River)
[RD20]	NOV-FE-0899-NT-105	TD-12 FRM Campaign logs: Installation of vorteX.io Micro-Stations over the Seine Estuary in Honfleur
[RD21]	NOV-FE-0899-NT-115	TD-12 Campaign logs: Drone campaign on the Po River
[RD22]	NOV-FE-0899-NT-118	TD-12 Campaign logs: Drone campaign on the Seine Estuary
[RD23]	Sheng, Y., C. Song, J. Wang, E.A. Lyons, B.R. Knox, J.S. Cox, and F. Gao. 2016. Representative lake water extent mapping at continental scales using multi-temporal Landsat-8 imagery. Remote Sensing of Environment, 185: 129-141, DOI:10.1016/j.rse.2015.12.041.	
[RD24]	Pottier C., "Auxiliary Data Description Document - Prior Lake Database (LakeDatabase)," CNES SWOT-IS-CDM-1944-CNES, 2022.	
[RD25]	Pekel, Jean-François, et al. "High-resolution mapping of global surface water and its long-term changes." Nature 540.7633 (2016): 418-422.	
[RD26]	Nielsen, K., Stenseng, L., Andersen, O. B., Villadsen, H., & Knudsen, P. (2015). Validation of CryoSat-2 SAR mode based lake levels. Remote Sensing of Environment, 171, 162-170.	
[RD27]	Cancet M., F. Lyard, F. Toublanc, L. Pineau-Guillou, E. Sahuc, E. Fouchet, G. Dibarboure, N. Picot (2021) The RegAt high-resolution regional tidal model in the North-East Atlantic Ocean: implementation and examples of applications. NOV-FE-1277-NT-002	
[RD28]	Chevallier, L. (2014). Caractérisation et modélisation de la variabilité hydrologique de l'estuaire de la Seine dans le cadre de la future mission spatiale SWOT. Université de Rouen Normandie. 14/ROUE/S057.1 vol. (362 p.)	
[RD29]	Lyard, F. H., Allain, D. J., Cancet, M., Carrère, L., and Picot, N.: FES2014 global ocean tide atlas: design and performance, Ocean Sci., 17, 615–649, https://doi.org/10.5194/os-17-615-2021, 2021.	
[RD30]	Lynch, D. R. and Gray, W. G.: A wave equation model for finite element tidal computations, Computers & Fluids, 7, 207–228, https://doi.org/10.1016/0045-7930(79)90037-9, 1979.	
[RD31]	MNT SHOM (2015). MNT Bathymétrique de façade Atlantique (Projet Homonim). http://dx.doi.org/10.17183/MNT_ATL100m_HOMONIM_WGS84	

Table of contents

1 Introduction

1.1 Purpose and scope

This document is the FRM Campaign Final Report for the "Sentinel-3 Topography mission Assessment through Reference Techniques (St3TART)" project, [RD1].

It is provided, as deliverable TD-13, at the Final Review (FR) of the project.

It describes the satellite validation approach, and the results obtained and the findings/conclusions following all the realized campaigns.

1.2 Overview of this document

In addition to this Introduction chapter, this FRM campaign final report includes the following chapters:

- CalVal "super site" on the Canal du Midi (Trèbes)
- CalVal "super site" on the Garonne River
- CalVal "super site" on the Maroni River
- CalVal "super site" on the Rhine River (French part)
- CalVal "super site" on the Rhine River (German part)
- CalVal "super site" on the Po River
- CalVal "super site" on the Tiber River
- CalVal "super site" on the Seine estuary in Honfleur
- CalVal "super site" on the Issykkul Lake
- CalVal opportunity sites

2 Canal du midi

2.1 Campaign performed on the site

On the “Trèbes” site we performed a campaign to install an in-situ sensor on the “Canal du Midi” under the Sentinel-3A track. This site was chosen because the "Canal du Midi" is a narrow canal with a controlled water surface height, an ideal geometry (the canal is perpendicular to the Sentinel-3 track) and is therefore an ideal case to evaluate the best possible performances that can be achieved by Sentinel-3. The station is installed on a bridge crossing the “Canal du Midi”. Further explanations on the choice of this site are given in the TD-6 document [RD6]. The full campaign is described in the corresponding campaign log [RD13]. The campaign was performed the 30/05/2022, the time-series is available since this date.

The first step of the data analysis is the computation of the reference height of the Micro-Station from the GNSS measurements recorded by the Septentrio base. This procedure is described in the TD-12 document associated with the campaign [RD13].

The PPP positioning of the base provides excellent results with a median height of **133.943 m (WGS84)** and a standard deviation of **1 cm**. During this GNSS measurement the base tracked **14 satellites** in average. The quality of the GNSS measurement is excellent. The rope access technicians have measured a vertical distance between the Micro-station and the centre of phase of the GNSS base of **1.915 m**. This gives a reference height for the Micro-station of **132.028 m** in ellipsoidal height, that corresponds to an altitude of **84.686 m (IGN 69)** after applying the French geoid.

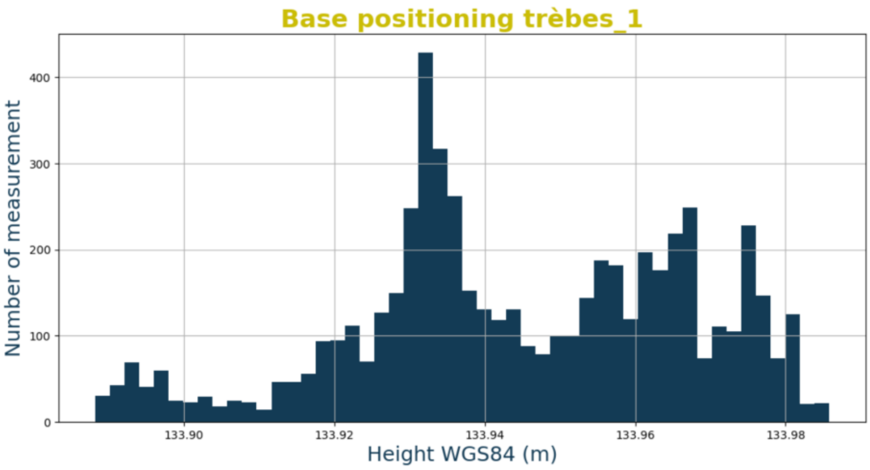


Figure 1: Histogram of the altitude of the base computed by PPP during the installation

The combination of this GNSS processing and the LiDAR measurements provides the precise altitude of the water measured by the Micro-Station. The time-series measured by the Micro-Station “trèbes_1” is described below (Figure 2).

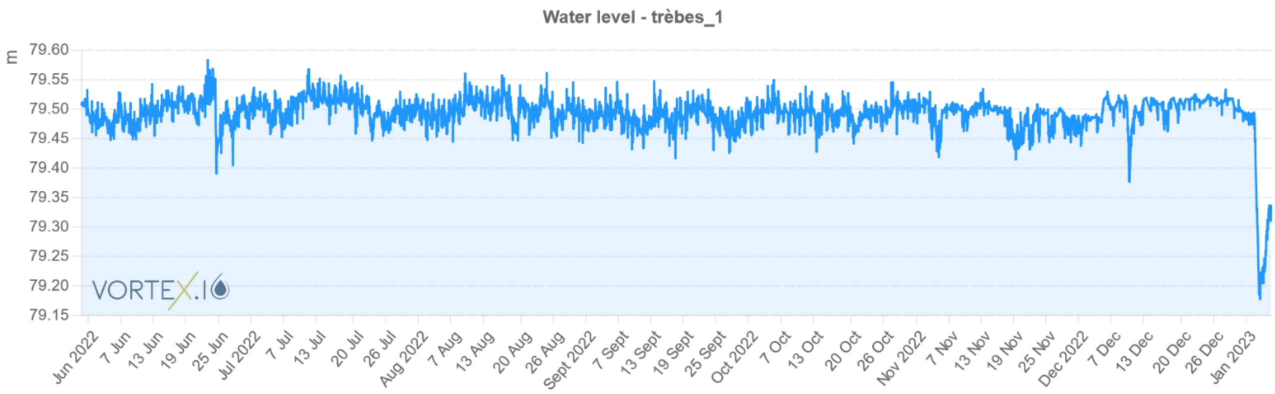


Figure 2: Time series of water surface height measured by the station labelled "trèbes_1" since the installation

The water surface height on “trèbes_1” is very stable, as expected. The “Canal du Midi” is not a free water body, and its level is controlled. The quality of the data is excellent. We can observe a drop of the water elevation the 2nd of January. This brutal evolution of the water height is due to hydrological control on the “Canal du Midi”. The pictures taken by the micro-station confirmed this (Figure 3).

Figure 3: Images taken by the micro-station "trèbes_1" before the decrease of the water level on the left and after it on the right

We can see on these pictures a difference in the water level. On the left the water level is higher than on the right. The picture on the left has been taken before the brutal drop and the one on the left just after. The pictures taken by the Micro-Station are very useful to understand the behaviour of the waterbody.

2.2 Computing FRM on the Canal du Midi

2.2.1 Computing the FRM

Following the Cal/Val site classification detailed in part the TD-6 document (RoadMap) [RD6], this site corresponds to a complexity level 0 site. Thanks to the installation of the instrumentation described in the previous paragraph: a vorteX.io Micro-Station, and following the recommendations related to this site class, we can compute the FRM measurement and then compare to Sentinel-3 data.

As mentioned before this site corresponds to a complexity level 0 site. The in-situ sensor is installed just under the satellite ground track. The computation of the FRM is very simple: there is no slope to be accounted for, no other in-situ data required, the measurement of the in-situ sensor can be performed at the exact same time as the satellite pass. The FRM simply corresponds to the measurement of the vorteX.io Micro-Station that has been configured to perform a measurement at the exact time of the Sentinel-3 pass for the ground track #16. The Equation of the FRM on this site is:

$$\boldsymbol{WSH_{FRM}(t)} = \boldsymbol{WSH_{IS}(t)}$$

2.2.2 Comparison with Sentinel-3

This exercise has been performed by CLS. The FRM is computed as described in the TD-6 document [RD6].

The comparison is performed following the steps described below:

1. Extraction of the water target of interest in the Carthage database (French river mask database)
2. Selection of the nearest data to the target centreline (coloured points) for each transect (cf Figure 4)
3. Computation of WSH for S3 and selection of in-situ measurement at the same time
4. Computation of Root Mean Square Error (RMSE) between the two timeseries

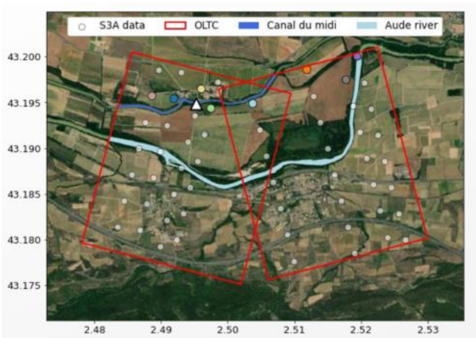


Figure 4: Selection of the Sentinel-3 measurements for comparison to FRM on the Trèbes site

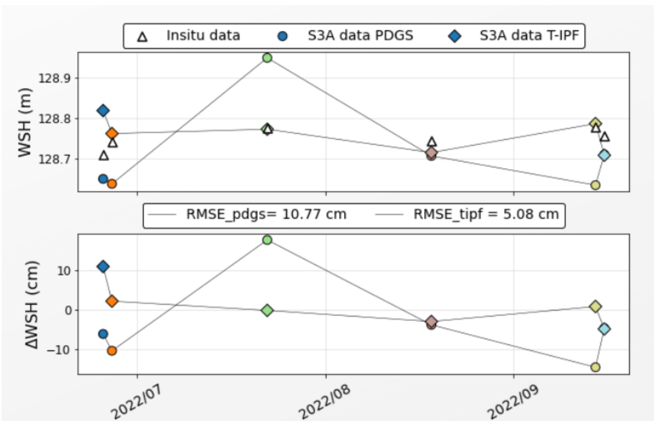


Figure 5: Comparison between FRM and Sentinel-3 measurements on the Trèbes site

The results obtained by CLS on the comparison between the FRM on the Trèbes site and Sentinel-3A data is about 10 cm of RMSE for L2 PDGS products and **5.08 cm of RMSE with the new Sentinel-3 Thematic hydro products**, which depicts the excellent performance of Sentinel-3A on this site, in accordance with the Mission Requirements.

The comparisons on the next cycles for the **L2 PGDS** products have been performed by vorteX.io team. The next Figure presents the comparison between the vorteX.io Micro-station and Sentinel-3A measurements.

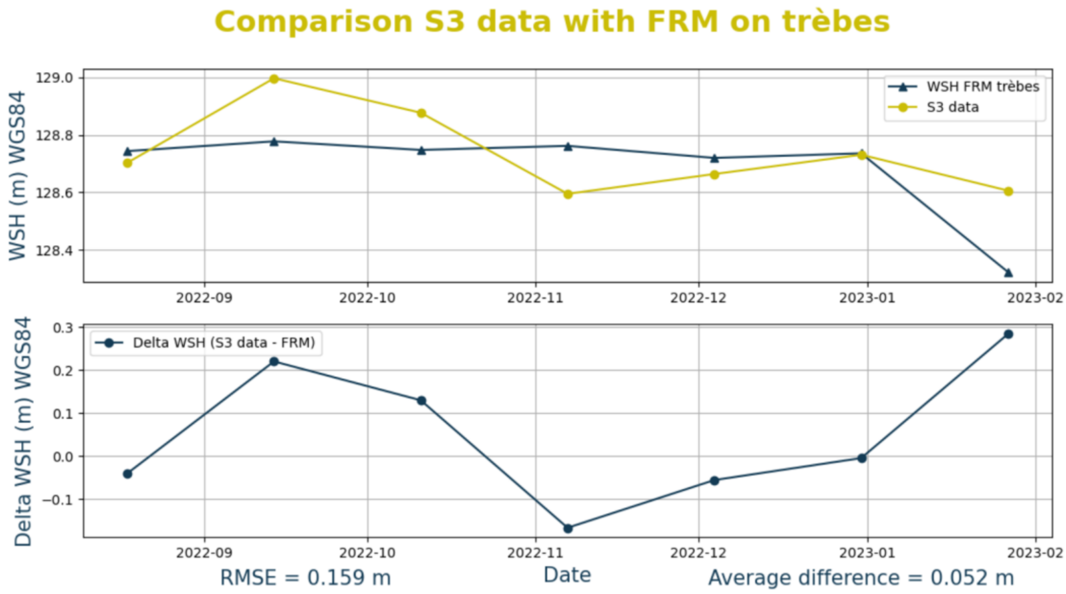


Figure 6 Comparison between FRM and Sentinel-3 measurements on the Trèbes site on the following cycles

The results obtained are excellent, with **16 cm RMSE** for the **L2 PDGS** products with **5 cm Average difference (also called bias)**.

On level 0 sites we are not correcting the excursion of the satellite. When we have a slope measurement (complexity level equal or greater than 1), we correct the excursion of the satellite because we virtually move the FRM at the actual satellite measurement. On level 0 sites there is no slope measurement, the theoretical satellite ground track is just above the in-situ sensor, but due to the excursion, the actual position of the satellite measurement can be at a maximum of 250 meters of the in-situ sensor. Depending on the geometry of the river, this absolute distance can correspond to a higher distance in curvilinear abscissa. Depending on the topography of the site the error can highly increase between the in-situ sensor and the S3 measurement. If a hydrological control is very close to the in-situ sensor, depending on the excursion, the satellite and the in-situ sensor can measure the different sides of the hydro control. This will result into an error equal to the height of the hydro control. The FRM is not usable on sites with hydrological control.

On "Trèbes" super site, there is almost no slope because it is a canal. We are going to see if there is a correlation between the distance virtual station / In-situ sensor and the error. This study will be performed on several complexity level 0 sites to control if the excursion has a major impact on the error.

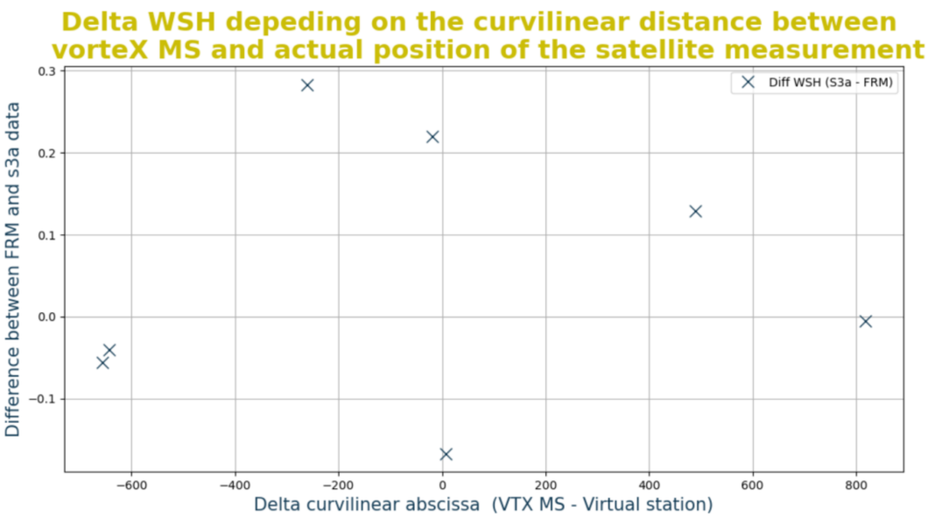


Figure 7: Difference between vorteX.io Micro-Station measurements and Sentinel-3A data depending on the distance between the actual position of the satellite measurement and the position of the Micro-Station

Regarding the previous graph, we can assume that there is no dependency between the difference of measurements and the distance between the actual position of the satellite measurement and the Micro-Station. This conclusion cannot be extended to every complexity level 0 super site (Or to the opportunity sites). We must perform the same study on other complexity level 0 super sites where the river topography is stronger than on the “Canal du Midi”, for example “Esslingen am Neckar” in Germany or “Deruta” in Italy. With the results on these 3 sites, we will have all the information to conclude on the dependency between the error and the distance to the Micro-Station.

2.2.3 Conclusions on the Trèbes site

The Trèbes site over the Canal du Midi represents an ideal case for Sentinel-3 performances. Indeed, the Canal du Midi is thin, flat, with a controlled level and a near perpendicular crossing geometry. Moreover, a bridge is located just below the Sentinel-3A tracks which is ideal to install an in-situ sensor such as the vorteX.io Micro-Station. With these conditions, the comparison leads to a RMSE of 10.77 cm between the vorteX.io Micro-Station and the standard Sentinel-3A L2 products and up to 5.08 cm with the thematical Sentinel-3 hydro products. This site should be maintained in the future, in particular to meet the long-term requirements on the MPC.

3 The Garonne River

3.1 Campaigns performed on the site

3.1.1 In-Situ sensors

The aim of the first campaign performed on the Cal/Val "super site" of the Garonne River near Marmande was to install 3 vorteX.io Micro-Station under bridges and complete this system with 5 pressure sensors. This "super site" has been chosen because of the presence of the Sentinel-3A tracks and because of the interesting topography of the site. A Sentinel-6 track also follows the Garonne River in this area. Further explanations on the choice of this "super site" are developed in the TD-6 document [RD6]. The full campaign is described in the corresponding campaign logs [RD10],[RD14]. A first installation campaign was performed on the 17/02/2022 to install the first Micro-Station in Marmande and one under a bridge at "Le Mas d'Agenais". A second campaign was performed on the 17/06/2022 to install a second Micro-Station in Marmande. All the time-series are available since the corresponding installation dates.

The first step of the data analysis is the computation of the reference height of the Micro-Stations from the GNSS measurements recorded by the Septentrio base. During the field campaign we performed the activities described in the TD-12 document ([RD10],[RD14]). The results were not satisfying for us, due to external perturbations. We chose to perform an additional GNSS measurement campaign, to ensure the quality of the Micro-Station positioning. To avoid the perturbation generated by the metallic bridges, we performed a measurement of the altitude of the water near the Micro-Stations. To do so, we installed the base just above the water and precisely measured the distance between the centre of phase of the base and the water surface. At the same moment the Micro-Station performed a measurement. With the PPP positioning of the base, the distance between the base and the water surface and the distance between the water surface and the Micro-Station, we can compute the precise altitude of the Micro-Station. We performed this GNSS measurement on each site. In the next paragraph we will present the results of the positioning of all the Micro-Stations and a short analysis of the data acquired since the installation.

"marmande_1":

The PPP positioning of the base provides good results with a median height of **60.396 m (WGS84)** and a standard deviation of **3 cm**. During this GNSS measurement the base tracked **11 satellites** in average. The quality of the GNSS measurement is good. The difference between the centre of phase of the GNSS base and the Micro-Station is **-13.202 m.** This distance has been computed from the Micro-Station LiDAR measurement and the distance measured between the GNSS base and the water surface. It results in a reference height for the Micro-Station of **73.598 m** in ellipsoidal height, that corresponds to an altitude of **26.749 m (IGN69)** after applying the French geoid

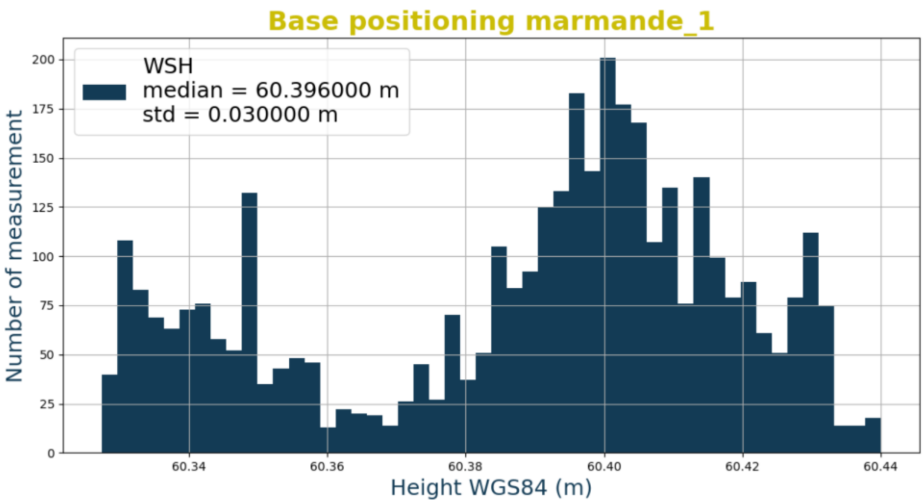


Figure 8: Histogram of the altitudes of the base computed by PPP for "marmande_1"

The combination of this GNSS processing and the LiDAR measurements provides the precise altitude of the water surface measured by the Micro-Station. We obtain the time-series measured by the Micro-Station “marmande_1” (Figure 9).

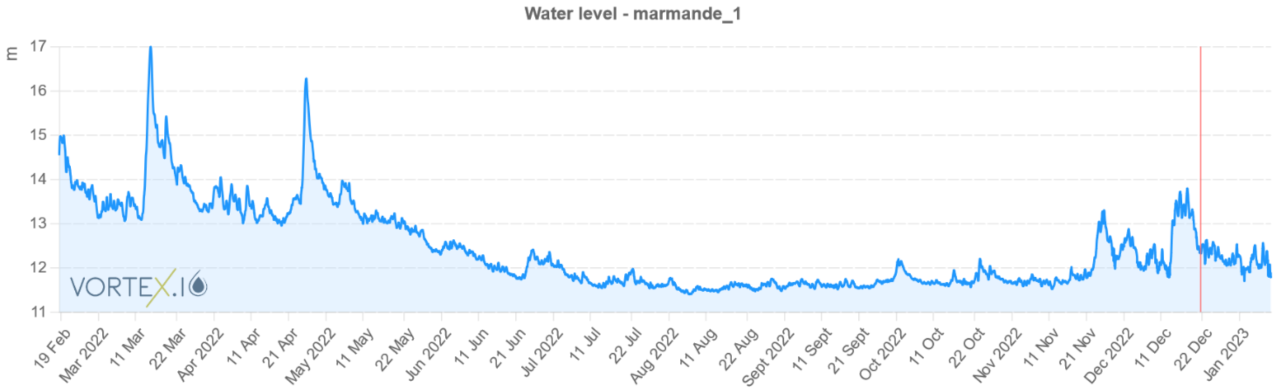


Figure 9: Time series of water surface height measured by the station labelled "marmande_1" since the installation

We can see the evolution of the Garonne River through the year. The measurements are very precise. We can see that the water level decreases from February to the beginning of July and then stay very stable until November. In November small flood events occurred but the average level of the Garonne River struggles to get back to its initial level. This enlightens the lack of precipitation and the big drought endured in the south of France in 2022. With few precipitations during fall, the drought continues in the winter. The Micro-Station has measured 2 main flood events between March and April. As expected, the Garonne River is a dynamic waterbody with a very different water height depending on the season.

“marmande_2”:

The PPP positioning of the base provides excellent results with a median height of **60.429 m (WGS84)** and a standard deviation of **1.9 cm**. During this GNSS measurement the base tracked **12 satellites** in average. The quality of the GNSS measurement is excellent. The difference between the centre of phase of the GNSS base and the Micro-Station is **-12.162 m.** This distance has been computed from the Micro-Station LiDAR measurement and the distance measured between the GNSS base and the water surface. It results in a reference height for the Micro-Station of **72.592 m** in ellipsoidal height, that corresponds to an altitude of **25.733 m (IGN69)** after applying the French geoid.

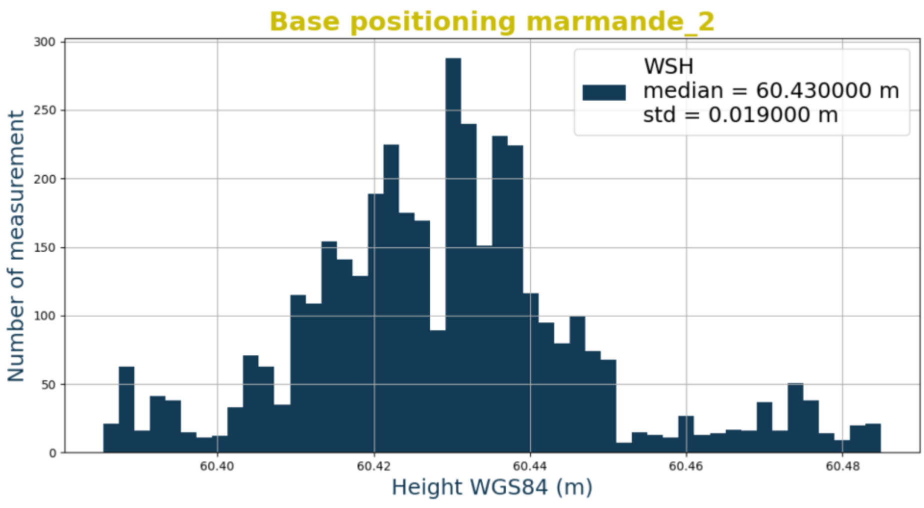


Figure 10: Histogram of the altitudes of the base computed by PPP for “marmande_2”

The combination of this GNSS processing and the LiDAR measurements provides the precise altitude of the water measured by the Micro-Station. We obtain the time-series measured by the Micro-Station “marmande_2” (Figure 11).

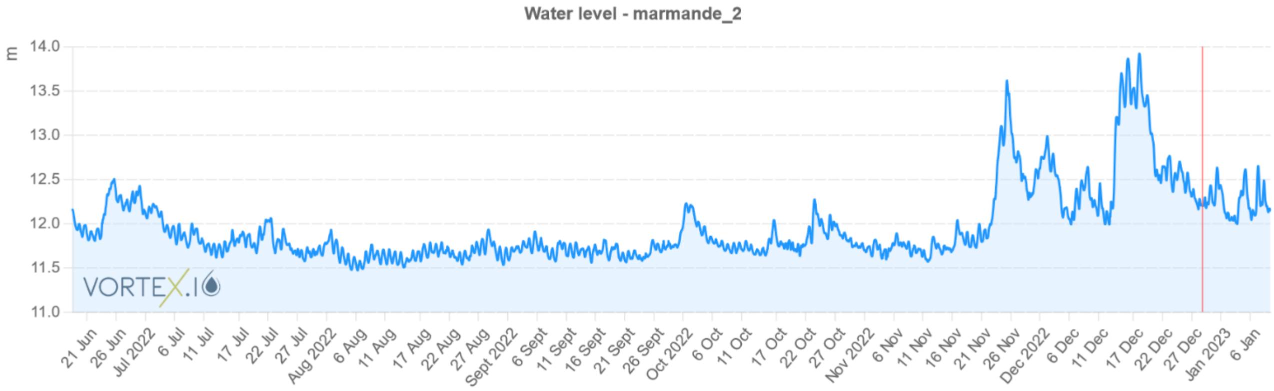


Figure 11: Time series of water surface height measured by the station labelled "marmande_2" since the installation

We can observe that the water height measured by “marmande_2” is like the one measured by “marmande_1”. “marmande_2” is few hundred meters upstream of “marmande_1”. This result is excellent, the 2 stations measure the same large-scale evolution with high precision. The main difference relies on small-scale oscillations measured by the upstream station. These oscillations seem to be attenuated when they reach the downstream station. The next figure (Figure 12) presents this phenomenon.

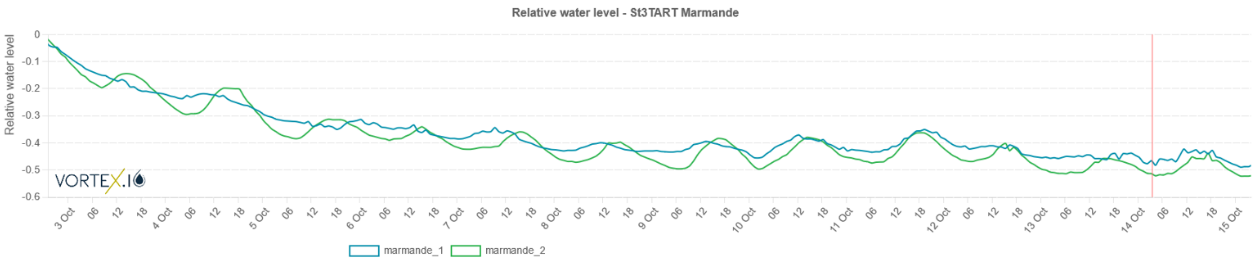


Figure 12: Water level anomaly measured by “marmande_1” and “marmande_2” between 03/10/2022 and 15/10/2022

We can observe these oscillations, their scale is around 10 cm. They seem to have a daily periodicity. We assume that these oscillations are related to a hydrological control near the upstream stations and attenuated between the 2 Micro-Stations.

Le Mas d’Agenais:

The PPP positioning of the base provides excellent results with a median height of **66.252 m (WGS84)** and a standard deviation of **2.2 cm**. During this GNSS measurement the base tracked **12 satellites** in average. The quality of the GNSS measurement is excellent. The difference between the centre of phase of the GNSS base and the Micro-Station is **-12.202 m.** This distance has been computed from the Micro-Station LiDAR measurement and the distance measured between the GNSS base and the water surface. It results in a reference height for the Micro-Station of **78.556 m** in ellipsoidal height, that corresponds to an altitude of **31.457 m (IGN69)** after applying the French geoid.

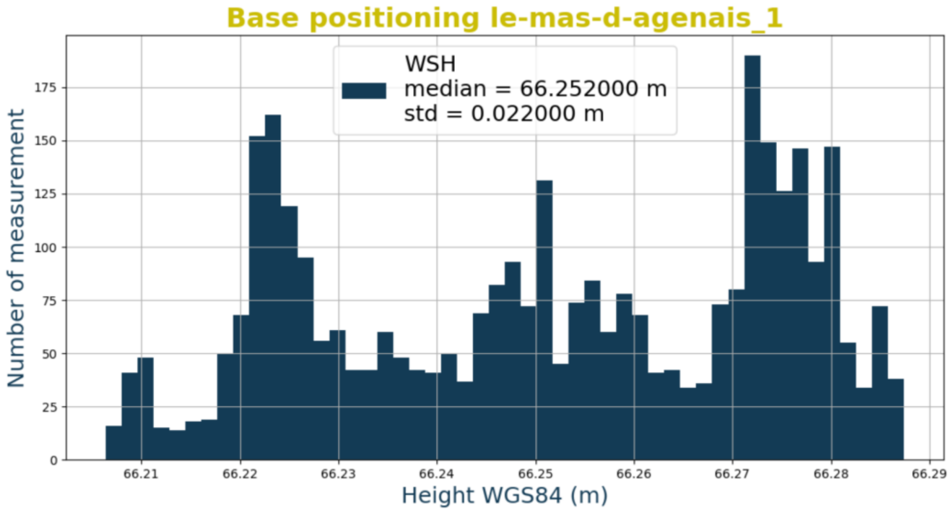


Figure 13: Histogram of the altitudes of the base computed by PPP for "Le Mas d'Agenais"

The combination of this GNSS processing and the LiDAR measurements provides the precise altitude of the water measured by the Micro-Station. We obtain the time-series measured by the Micro-Station "le-mas-d-agenais_1" (Figure 14).

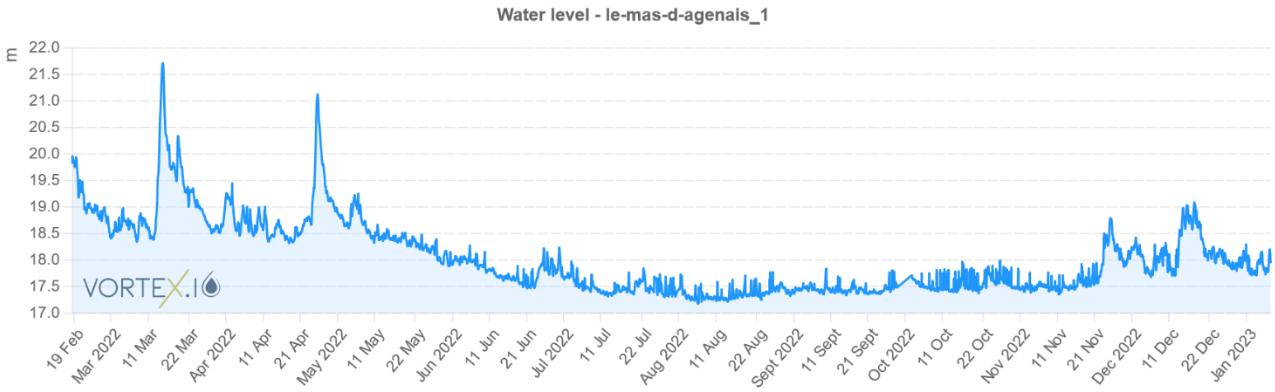


Figure 14: Time series of water surface height measured by the station labelled " le-mas-d-agenais_1" since the installation

This Micro-Station is installed 12 km upstream the 2 Micro-Stations in Marmande. We can observe the same water dynamic with a time lag. The measurements of this Micro-Station are noisier than the ones made by the other stations. We developed an editing algorithm to correct the noisy measurements. This algorithm improved the quality of the time-series. But even with this algorithm the measurements are still noisy. We chose to install a second Micro-Station just next to the old one to validate the measurements. The next figure (Figure 15) presents the water level anomaly of the 2 Micro-Stations in "Le mas d'Agenais" (located on the same bridge). Both Micro-Stations measure the same water surface altitude.

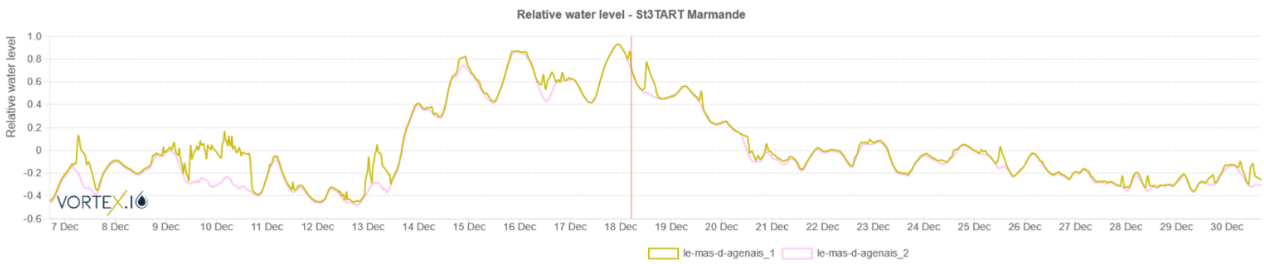


Figure 15: Water level anomaly measured by "le-mas-d-agenais_1" and "le-mas-d-agenais_2" between 07/12 and 31/12

The measurements of the new Micro-Station are not noisy. We will uninstall the first Micro-Station and investigate to understand the origin of this noise and solve it for our next version of the station. This problem only happened to this station.

Pressure sensors:

In the framework of the project pressure sensors have been installed all along the Garonne River on Marmande "super-site". Those pressure sensors have been installed by CNES, Hydro Matters and vorteX.io. The aim of the installation of these pressure sensors is to validate the measurements performed during the drone campaign by the light-weighted altimeter from vorteX.io. The pressure sensors have been installed on the 15 of September 2022. Those sensors have no connectivity and do not automatically transfer the measurement. In order to obtain the data, the team must go on the field and take the sensors out of the river. This field campaign has been performed in December. Only 3 of the 5 pressure sensors have been take out of the water. We only have the full time-series between September and December for these 3 sensors. For the 2 remaining sensors we currently have only 1 week of data. The next graphs present the location of the pressure sensors and the time-series measured by the pressure sensors displayed in the data visualisation platform Maelstrom.

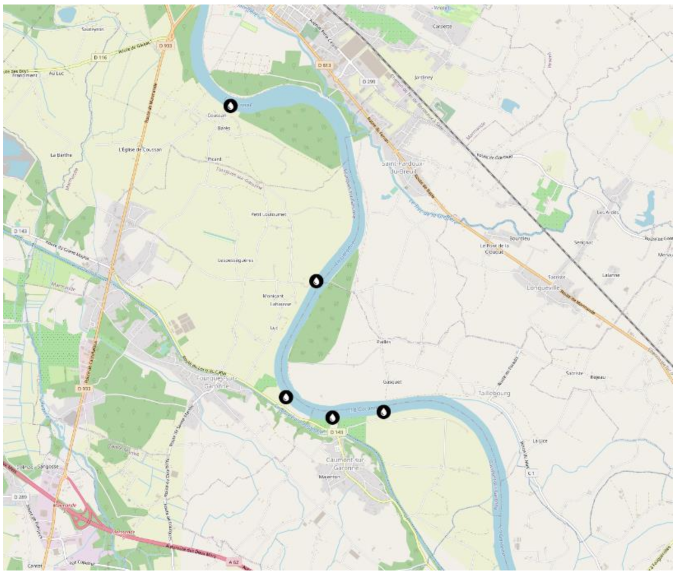


Figure 16: Location of the 5 pressure sensors on the Garonne River on the Marmande super-site.

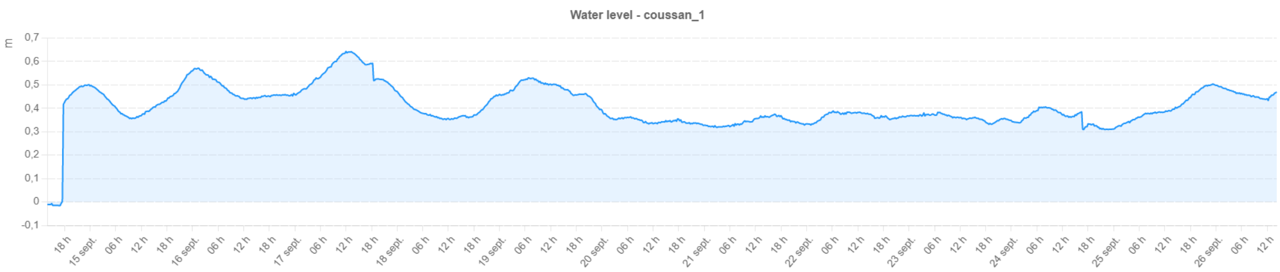


Figure 17: Time series of water surface height measured by the pression sensor labelled " coussan_1"

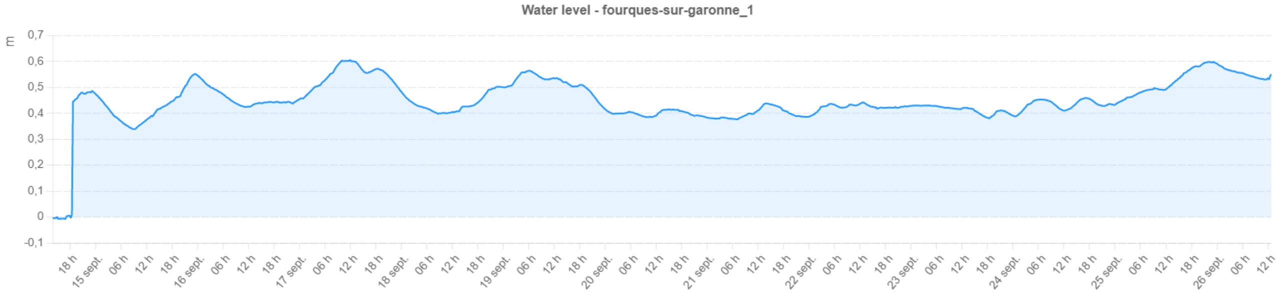


Figure 18: Time series of water surface height measured by the pression sensor labelled " fourques-sur-garonne_1"

Figure 19: Time series of water surface height measured by the pression sensor labelled " fourques-sur-garonne_2"

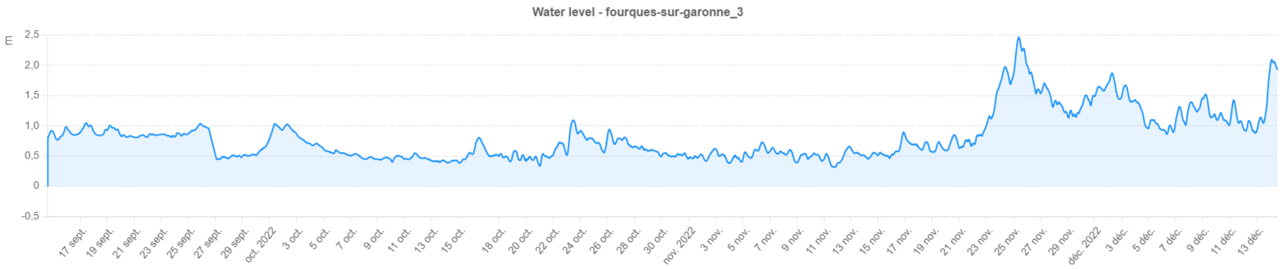


Figure 20: Time series of water surface height measured by the pression sensor labelled " fourques-sur-garonne_3"

Figure 21: Time series of water surface height measured by the pression sensor labelled " Caumont-sur-garonne_1"

The quality of the measurements is very good. Unfortunately, it is impossible for us to use the data to compare with moving sensor measurements yet. We must compute the altimetric reference of the pressure sensors to perform the comparisons.

3.1.2 Moving Sensor

As mentioned in the previous paragraph, the Garonne is a very dynamic river. The satellite ground tracks don't exactly overfly the Micro-Stations installed in the frame of the project. The topography of the river must be accounted to perform good FRM measurements. 2 campaigns have been performed to fulfil this objective and a last one is planned in the next months. The first campaign was performed on the 08/02/2022 and the second one was performed on the

28/06/2022. We chose those dates to measure the topography at different water levels. We assume that the topography of the Garonne River will be very different depending on the river stage. The campaigns are fully described in the corresponding campaign logs [RD9],[RD15].

In the next paragraph we present the results of the 2 campaigns performed by the vorteX.io team in partnership with a drone pilot company I-TECHDRONE. As for the Micro-Stations, the first data analysis we present is the positioning of the geodesic base and the positioning of the altimeter. Then we present the results of the data analysis of the LiDAR measurements. The procedure applied during these campaigns are described in the corresponding campaign logs [RD9], [RD15].

First drone campaign:

As explained in the campaign log documents ([RD9], [RD15]), in order to get the exact altitude of the water surface we need to compute the precise altitude of the altimeter embedded under the drone. To do so, we perform PPK positioning with a geodesic base as reference. The first step in the data processing is to perform the PPP of the base from its GNSS measurements. The positioning of the base is very precise with a standard deviation of **4 mm.** The base altitude is **68.092 m (WGS84).** With this very precise base positioning, we'll have good results for the positioning of the altimeter.

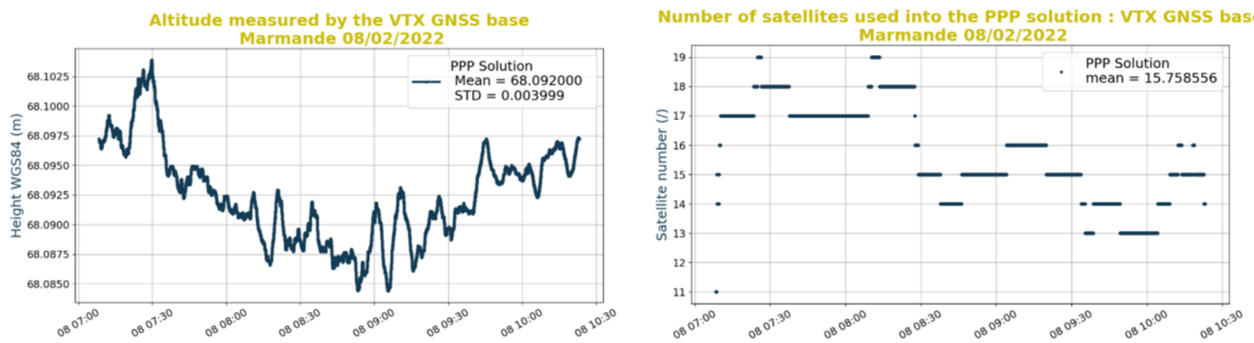


Figure 22: PPP positioning of the base on the left and the number of satellites tracked by the base on the right

During the campaign a manipulation error occurred, the base was shut down at **10:30 AM.** To substitute our base, we used data from the French Network of GNSS base **(RGP)**. 3 bases are available in the area and their GNSS measurements are in open data as shown in Figure 23. We performed a PPP processing for the 3 bases. Then we performed 3 PPK positioning for each flight performed after 10:30 AM with each base as reference. Finally, we computed the mean of the 3 positioning to ensure better results. We are less confident in these positioning due to an inter receptor bias between our altimeter and the GNSS bases. The computation of the mean of the 3 positioning helps to decrease this bias.

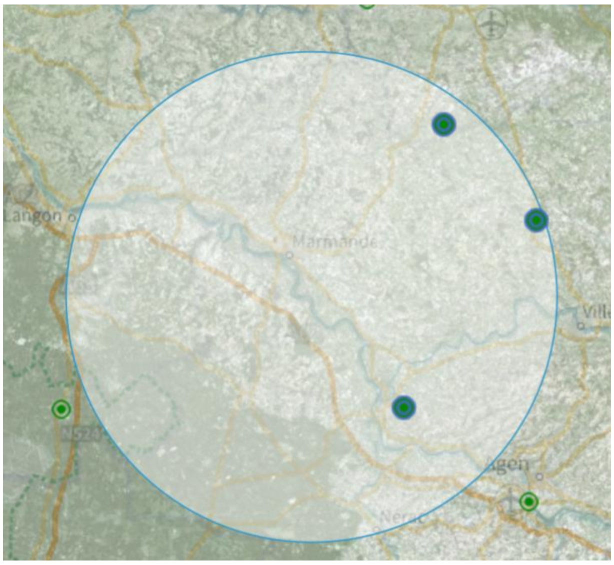


Figure 23: Position of the 3 bases used to perform PPK positioning of the altimeter

With the precise positioning of vorteX.io and RGP bases we have computed the precise positioning of all the flights performed on the Garonne River. The positioning of the drone during all the flight is excellent when we have the vorteX.io base as reference. For the other flights the quality of the positioning is good, the mean of the positioning ensures us that the inter receptor bias mitigate impacts on the results. The next figure (Figure 24) presents the altitude of the altimeter during one flight.

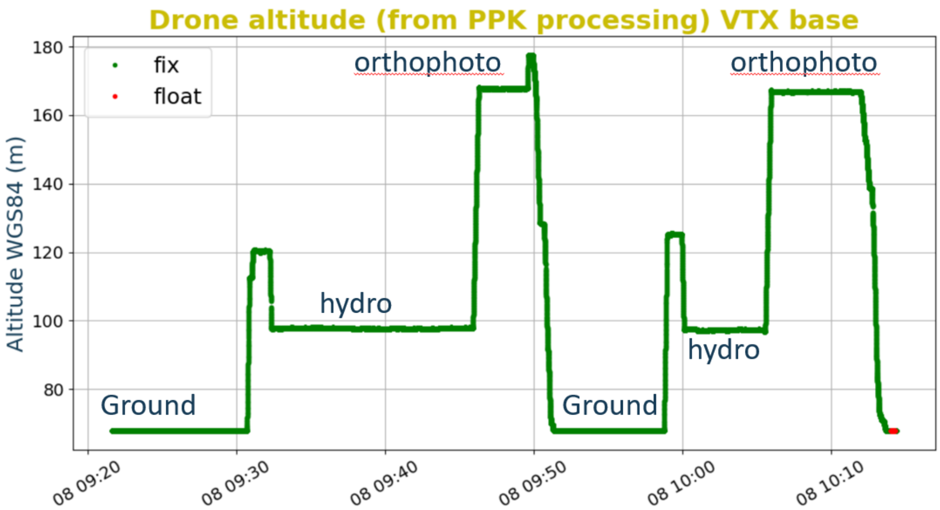


Figure 24: Altitude of the altimeter during the first flight

All the ambiguities are fixed during the flight and the altimeter has tracked **15** satellites. We have performed 2 types of flights during this campaign, hydrological flights to measure the altitude of the water surface with the LiDAR and orthophotos flights to map the area with the images taken by the altimeter camera. To perform orthophotos flights we chose to fly higher to get a bigger field of view of the river.

Once the precise positioning computed, we can compute the water surface height from the LiDAR measurements. We have applied a running mean (window of 15 seconds) on the WSH measured by the altimeter to decrease the measurement noise. The LiDAR measurements are performed at 7 Hz, and we finally resampled to 0.5 Hz for the data dissemination.

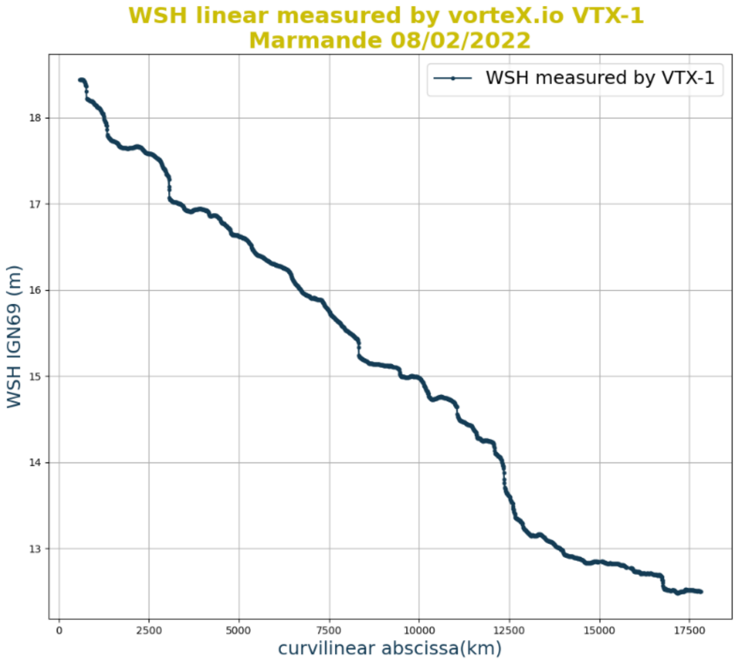


Figure 25: Water profile measured by vortex.io altimeter on the Garonne River during the 08/02/2022

We can see that there are a lot of discontinuities on this profile due to the presence of waterfalls and pools. Therefore, the importance of a good knowledge of the river topography is clearly highlighted by this first result. The slope between the in-situ sensors is not linear and it is thus important to know the different behaviours of the river slope/topography depending on the water surface height to correct the in-situ measurements and to provide good FRMs.

Second drone campaign:

The position of the base is obtained by performing a PPP (Precise Point Positioning) processing. The obtained position of the base is very precise, with a standard deviation lower than **5 mm**, as shown in Figure 26. The number of satellites tracked by the GNSS base during the acquisition time is around **16** in average. The satellites of the GALILEO, GPS and GLONASS constellations are used to perform the positioning. The quality of the positioning is very good. The base position is **69.936 m (WGS84)**.

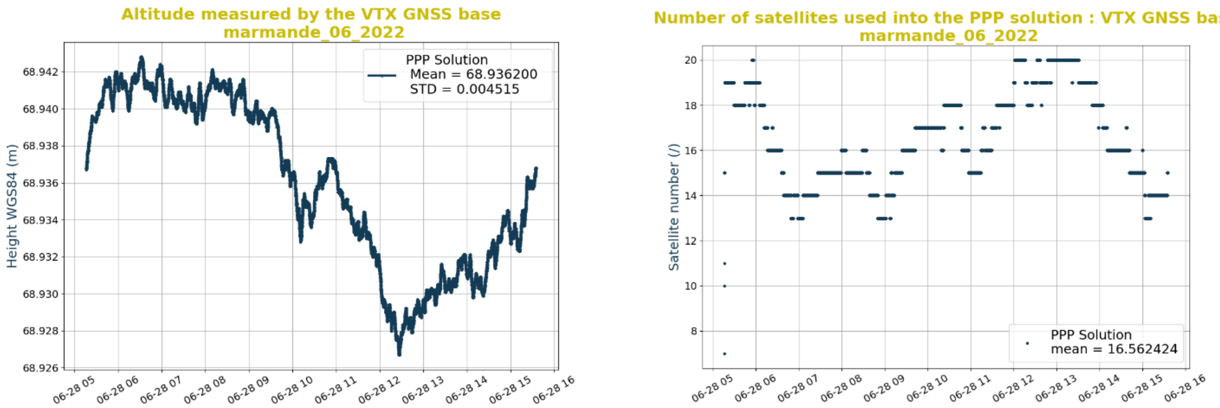


Figure 26: PPP positioning of the base on the left and the number of satellites tracked by the base on the right

Once the precise position of the base is computed, we can perform the PPK positioning of the altimeter. All the ambiguities are fixed when the altimeter is flying and thus the positioning is of good quality. We can see in Figure 27 the evolution of the altimeter altitude during the first flight of the campaign. This precise positioning allows to get a precise water surface height measurement. The main difference with the previous campaign is the drone altitude. We only performed hydrological flights and kept a flying altitude around 50 m above the water surface.

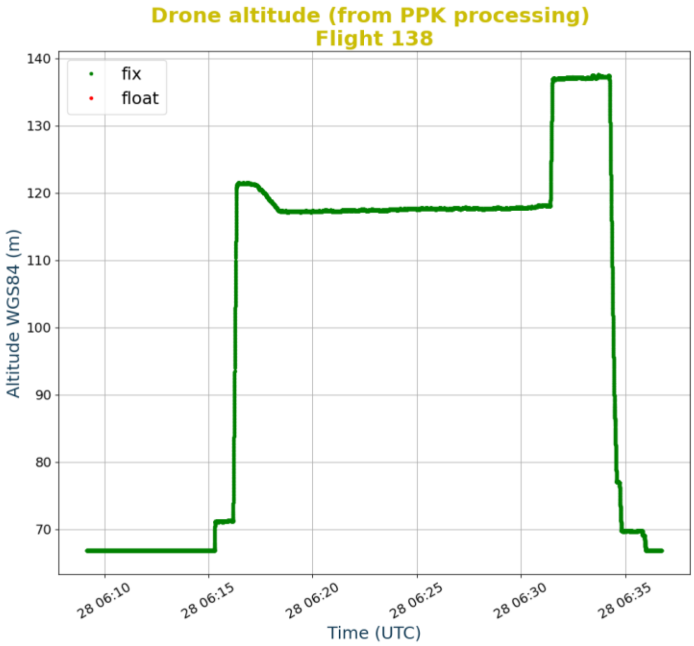


Figure 27: Altitude of the altimeter during the first flight

Once the precise positioning computed, we can compute the water surface height from LiDAR measurements. We have applied a running mean (window of 15 seconds) on the WSH measured by the altimeter to decrease the measurement noise. The LiDAR measurements are performed at 7 Hz, and we finally resampled to 0.5 Hz for the data dissemination.

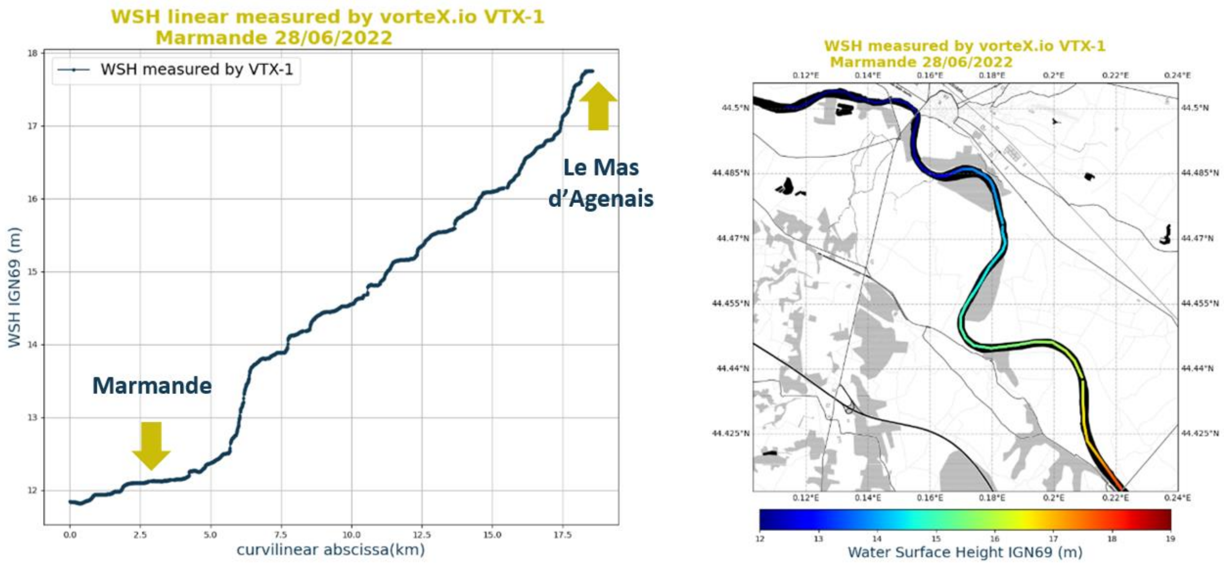


Figure 28: Water surface height profile measured by vorteX.io light altimeter during the campaign

The results of this second campaign confirmed the one obtained by the first campaign. We can see a lot of discontinuities on this profile due to the presence of waterfalls and pools. The topography seems to be different than in February. The next figure (Figure 29) is the comparison of the two river profiles.

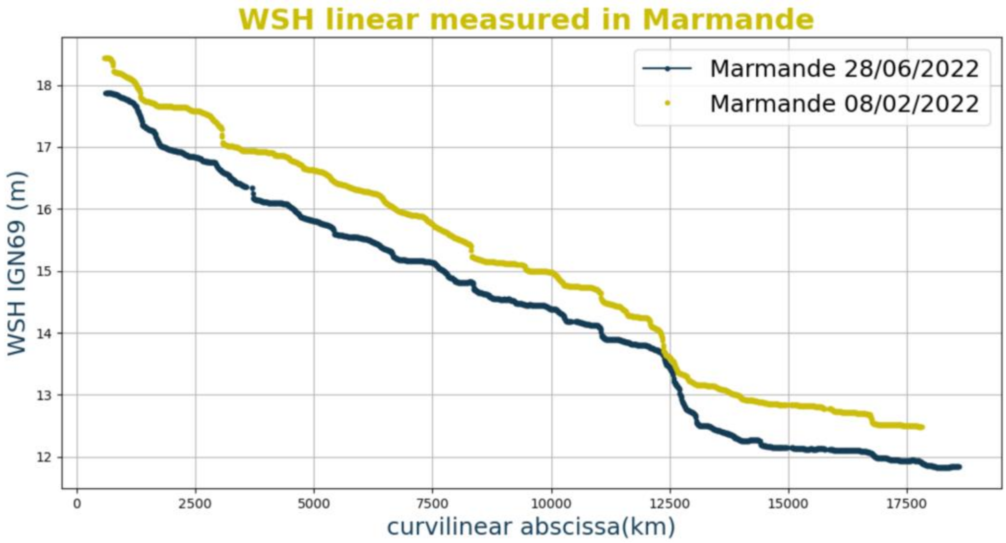


Figure 29: Comparison of the 2 river profiles performed on the Marmande site

On this figure we can see the main differences between the 2 profiles measured during the 2 campaigns. The average water level is higher in February than in June. The topography of the Garonne is different between the 2 campaigns. As expected, there are more pools and jumps on the profile measured in June. This result enlightens the necessity to perform multiple drone campaigns at different water heights to measure the differences in the river topography. With more than one profile it is also possible to interpolate between the measured profiles to estimate the profile at a specific water height.

3.1.3 Summary of the campaign

To summarize, on the Marmande super site over the Garonne River, we have installed in the frame of the St3TART project 3 Micro-Stations (“marmande_1”, “marmande_2” and “le-mas-d-agenais_1”) as illustrated on the map on Figure 30, we performed 2 drone campaigns funded by CNES (the last one will be performed in the beginning of 2023 at high water level) and installed 5 pressure sensors (also funded by CNES, in kind contribution).

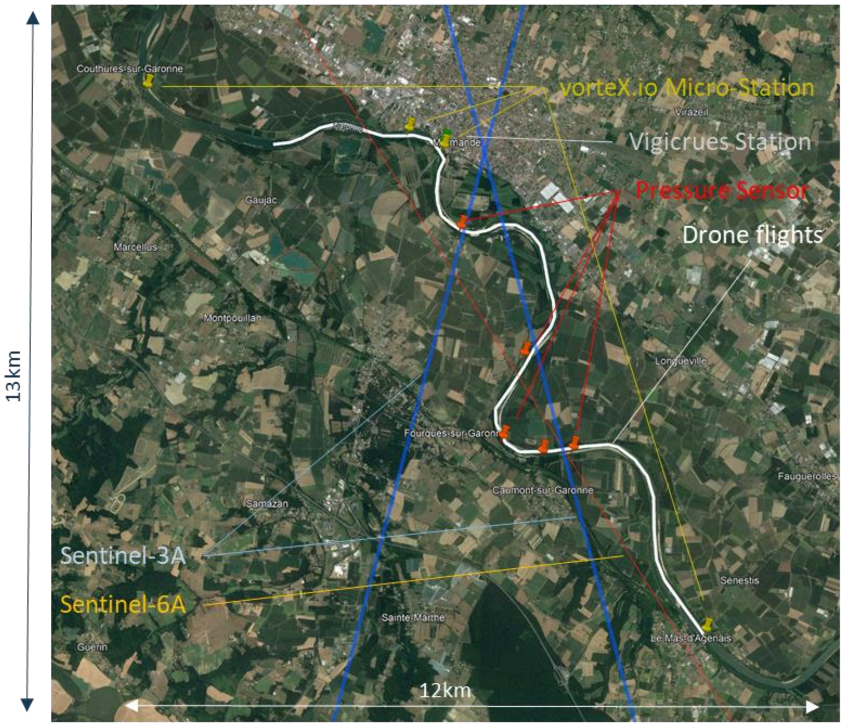


Figure 30: Map of the Marmande Cal/Val super site with all the instrumentation installed

An additional drone flight is planned in the frame of the project in the next months. We are waiting for the rise of Garonne level to perform this additional drone campaign.

3.2 Computing FRM on the Garonne River

3.2.1 Computing the FRM

Following the Cal/Val site classification detailed in the TD-6 document (RoadMap) [RD6], this site corresponds to a complexity level 3 site. Thanks to the installation of the instrumentation described in the previous chapters: 3 vorteX.io Micro-Stations and 2 drone campaigns, and following the recommendations related to this site class, we can compute the FRM measurement and then compare to Sentinel-3 data.

As mentioned before this site corresponds to a complexity level 3 site. The in-situ sensor is not installed just under the satellite ground track. First, we need additional in-situ data to compute the time lag between the virtual station and the in-situ sensor. The Micro-Station will perform its measurement at $\boldsymbol{t+\delta_t}$. The topography of the Garonne River is complex, we need to take into account the slope. The FRM corresponds to the measurement of the vorteX.io Micro-Station that has been configured to perform a measurement at the exact time $\boldsymbol{t+\delta_t}$ corrected from the slope measured by the moving sensors. This slope topography must be corrected from the evolution of the water level during the campaign. The Equation of the FRM on this site is:

$$\boldsymbol{WSH_{FRM}(t) = WSH_{IS}(t+\delta_{ts}) + \left(\Delta WSH_{slope} - Corr_{evo\_tempo}\right)}$$

with $\boldsymbol{\Delta WSH_{slope} = WSH_{moving\_sensor\_at\_SGT} - WSH_{moving\_sensor\_at\_IS}}$

and where $\boldsymbol{WSH_{moving\_sensor\_at\_IS}}$ corresponds to the moving sensor measurement next to the in-situ sensor and

$\boldsymbol{WSH_{moving\_sensor\_at\_SGT}}$ to the moving sensor measurement at the actual position of the satellite ground track. $\boldsymbol{Corr_{evo\_tempo}}$ corresponds to the correction related to the spatial and temporal evolution that we apply on the moving sensor measurements to correct the water level evolution of the river during the campaign time.

Prerequisites:

1. The centreline

A river centreline is needed for the FRM processing on the Garonne River. This centreline is computed from the TOPAGE database (French river database) or can be computed from a kml file built from a Google Earth trajectory. The centreline is the curvilinear abscissa along the river. The computed centreline of the Garonne River is shown in Figure 31.

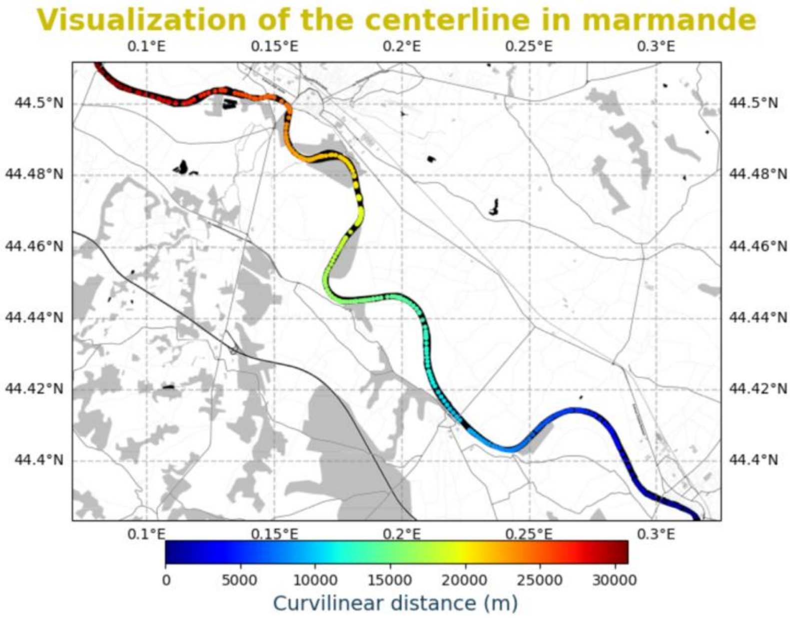


Figure 31: Visualisation of the centreline in Marmande

2. River topography measurements

As mentioned before, 2 drone campaigns have been performed on this site to measure the river profile at 2 different water levels. A first on the 08/02/2022 and the second on the 28/06/2022. The 2 measured river profiles are shown in Figure 29.

3. Compensate the river profiles measured during the drone campaigns from the water level evolution

The river profile is not measured as a snapshot (the campaign takes ~2 hours to complete), the river profile measured by the drone must be corrected from the water evolution of the Garonne River during the campaign time. To do so, in-situ stations are used. As the first drone campaign was performed before the installation of the Micro-Stations, we use the Vigicrues stations (stations from the SCHAPI, the French national in-situ network) to correct the river profile from the water level evolution. First, we compute the average propagation time between 2 Vigicrues stations located on either side of the area of interest: Tonneins and Marmande. We consider a period of 2.5 days before and after the campaign time and estimate the time lag between the two time-series of water level anomaly (the mean value is subtracted on both time series) using an algorithm that maximises the cross-correlation between the two time-series.

The time lag computed for the first campaign is shown in Figure 32.

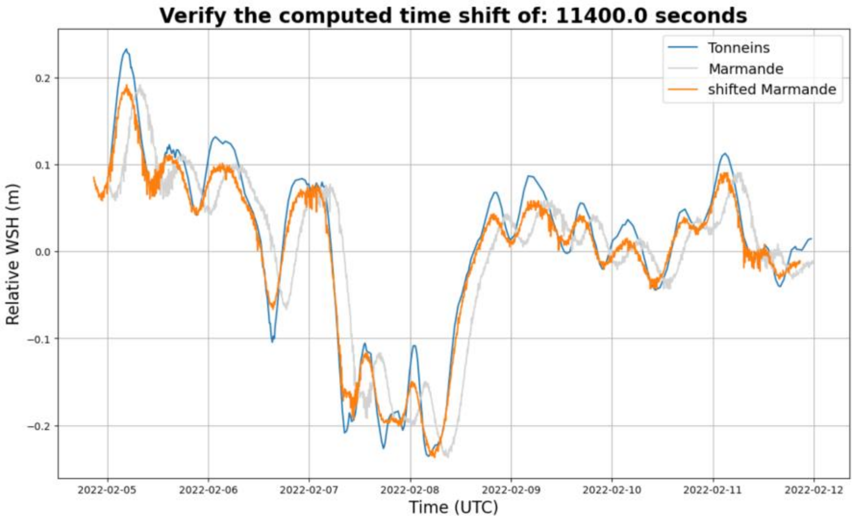


Figure 32: Time lag computed for the first campaign. The Tonneins water level anomaly is in blue, the Marmande one is in grey and the Marmande one corrected from the computed time shift is in orange

With the computed time shift, the average flow speed is computed using the curvilinear abscissa of the centreline between the two stations. Then this average speed is used to compute the propagation time from the nearest station here Marmande) and each point of the river profile. Finally, we compute the water level evolution correction on each point of the river profile thanks to the computed propagation times and the height difference measured during the same time at the Marmande gauge. The corrected river profiles are presented in Figure 33 for both drone campaigns.

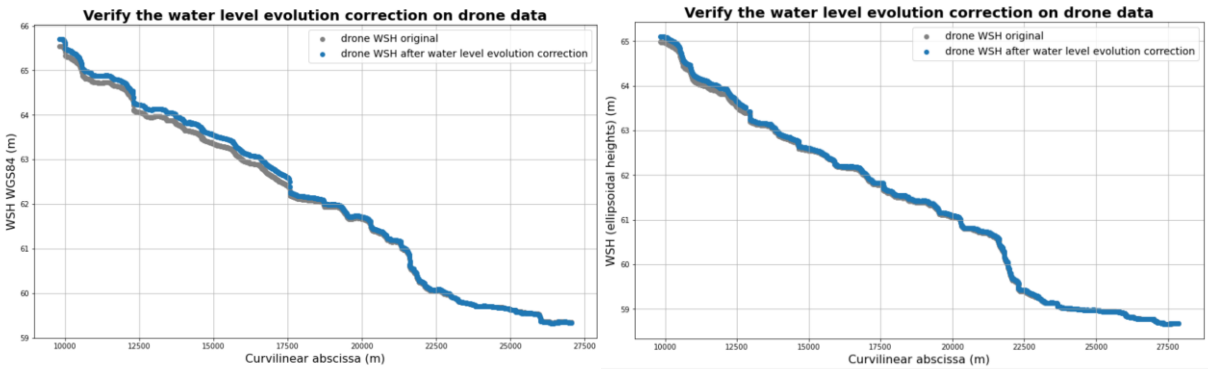


Figure 33: Comparison of the river profile before (in grey) and after (in blue) the water level evolution correction for the first drone flight (on the left) and the second one (on the right)

Then, each river profile is assigned a water level value: the water level corresponding to the Marmande gauge overflown by the drone.

3.2.2 Comparison with Sentinel-3

This exercise has been performed here by vorteX.io. The FRM is computed as described in the TD-6 document [RD6].

FRM Processing:

1. Load Sentinel-3 data and get the actual time *t* and location of the satellite measurements.

Sentinel-3 data are downloaded from the ESA Copernicus Open Access Hub (https://scihub.copernicus.eu/). The Figure 34 illustrates data from cycle 86 on the S3A ground track #444.

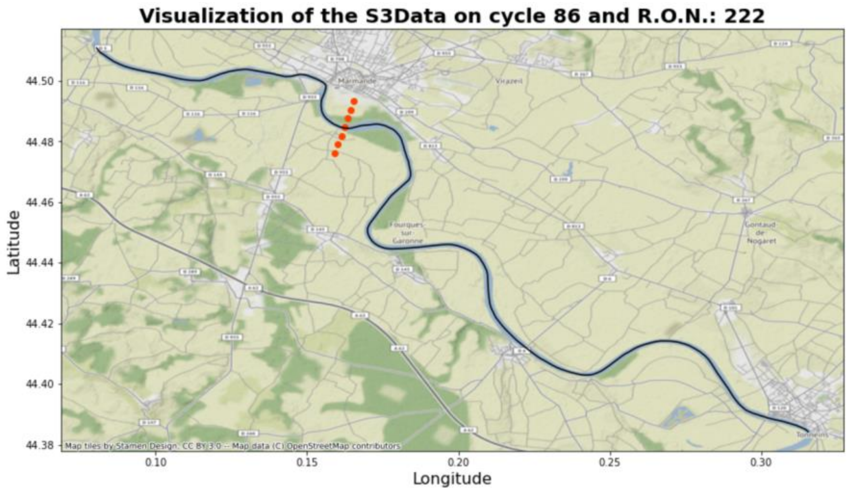


Figure 34: Map showing the positions of the S3A measurements on cycle 86 track #444 over the Garonne River

2. Compute the propagation time ***δt***

Then, the propagation time and the associated average flow speed are computed on this area and at the time of the satellite pass using the Micro-Stations installed on the field: marmande_1 and le-mas-d-agenais_1. This propagation time is computed with the same algorithm than the one presented for the river profile correction. On this example, the propagation time is estimated at 7200 seconds between the two Micro-Stations.

3. Compute the height at the reference station at ***t + δt***

The ellipsoidal height measured by the marmande_1 Micro-Station at ***t + δt*** is selected (or interpolated if the time does not correspond exactly, i.e. less than 1 minute).

4. Compute the slope correction from the drone profiles.

The slope correction corresponds to the **δh** between the drone height measured at the location of the Micro-Station Marmande_1 and the exact location of the actual Sentinel-3 measurement. To do so, an interpolation is performed between the 2 corrected river profiles. Each river profile corresponding to a water level, the interpolation of the river profile is done for the water level corresponding to the satellite pass (i.e. measured by the station at the time of the satellite pass + the propagation time).

5. Finally, the FRM value is computed combining the height at the reference station at ***t + δt*** and the slope correction.

The comparison between the FRM value and the Sentinel-3A measurement for cycle 86 is shown in Figure 35. The obtained difference is about 0.099 meters which is in line with the mission requirements.

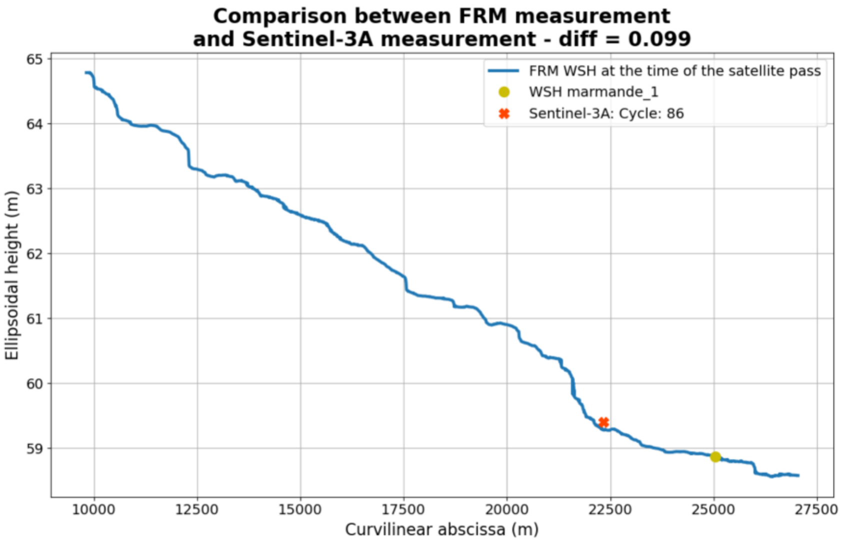


Figure 35: Comparison between the FRM measurement and the Sentinel-3 measurement in Marmande for cyle 86. The red cross corresponds to the Sentinel-3 water surface height (w.r.t. reference ellipsoid), the yellow dot correspond to the measurments of the marmande_1 Micro-Station at *t+δt*, and the blue line is the river profile added to the Micro-Station measurement to symbolize the FRM measurement.

The comparisons on the next cycles for the L2 PGDS products have been performed by vorteX.io team. The next Figure presents the comparison between the vorteX.io Micro-station and Sentinel-3A measurements.

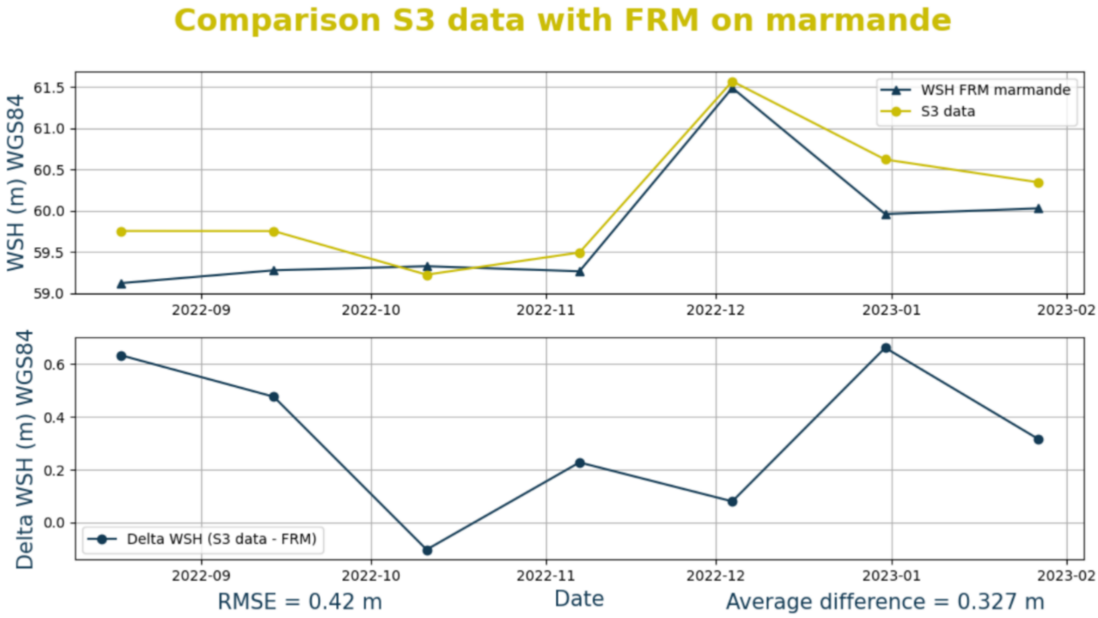


Figure 36: Comparison between FRM and Sentinel-3 measurements on the Marmande site for R.O.N.: 222

The results obtained are good, the **42 cm RMSE** is too high but the **L2 PGDS** products are not yet optimised for hydro measurements, indeed, the new thematic hydro products will be more relevant for this scope. We want to perform the comparison with the hydro thematic products to measure the difference between both products. The **average difference** is **32 cm,** this result is excellent.

On this super-site there is also a second track S3A ground track. We performed the comparison as presented on the previous paragraph with this second ground track. Due to the geometry of the site, the Sentinel-3A ground track crosses the Garonne River 3 times at 3 different locations. We compute the comparison for each virtual station. These 3 comparisons give information about the dependency between the error and the distance between the in-situ sensor and the virtual station. The following graphs present the result for this second ground track for the **L2 PGDS** products.

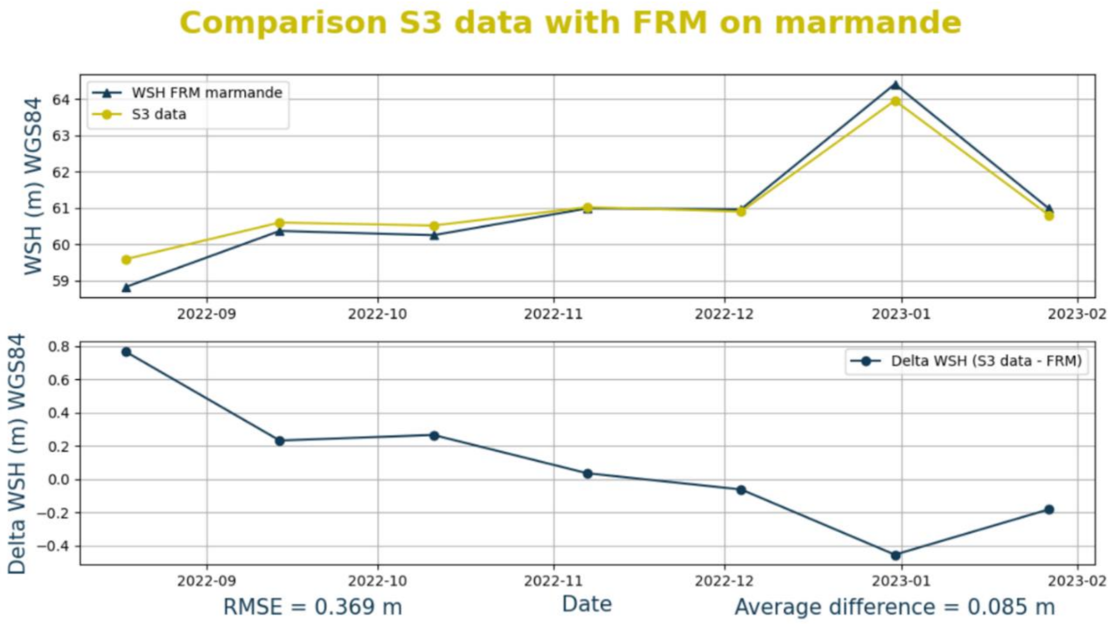


Figure 37: Comparison between FRM and Sentinel-3 measurements on the Marmande site for R.O.N.: 299, for the first virtual station

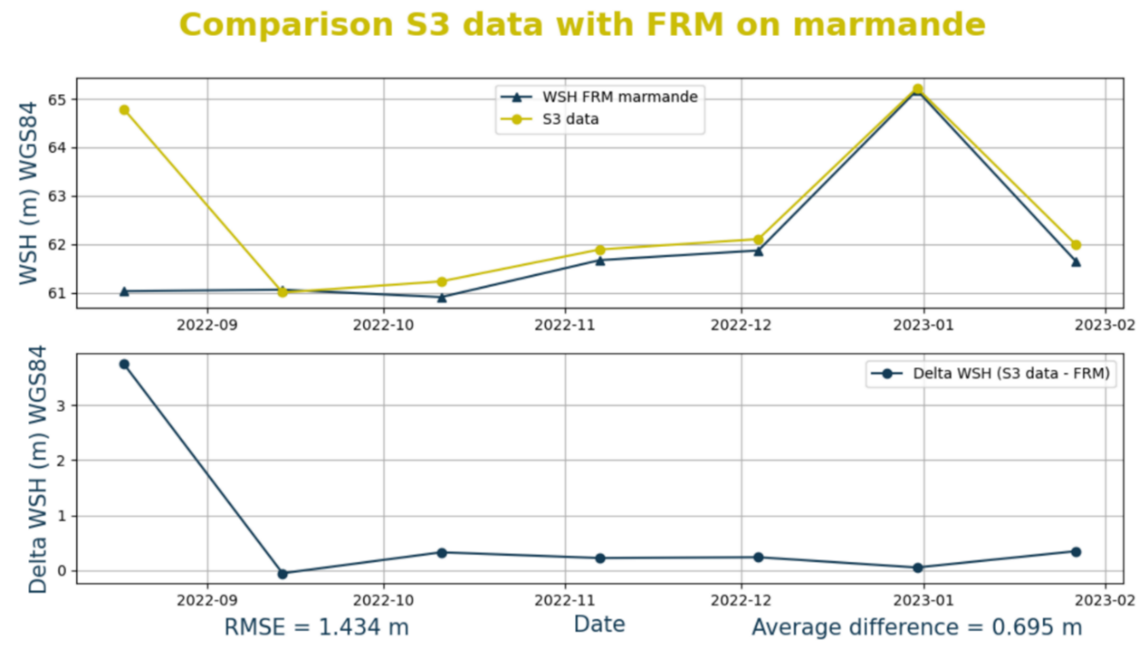


Figure 38 : Comparison between FRM and Sentinel-3 measurements on the Marmande site for R.O.N.: 299, for the second virtual station

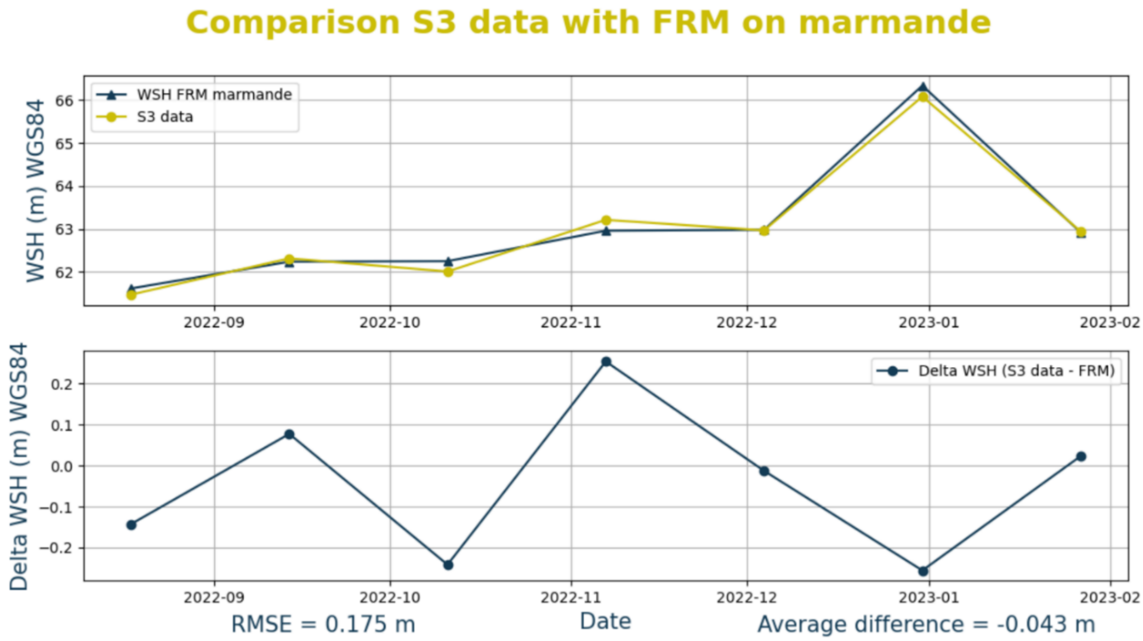


Figure 39: Comparison between FRM and Sentinel-3 measurements on the Marmande site for R.O.N.: 299, for the third virtual station

The results are excellent, we have a **RMSE** between **36 cm and 17.5 cm** for the **L2 PGDS** products that are not made for hydro measurements. On the second virtual station, the difference between the FRM and the satellite measurement for the first cycle processed is around 4 meters. The geometry of the super site can explain the difference. Due to the geometry of the Garonne River, on some cycles the satellite ground track can miss the river due to the excursion. On this specific cycle the satellite has not measured the Garonne on the second virtual station. We can confirm this result by looking at the comparisons performed on the first and third virtual station. For these 2 virtual stations the difference is under 1 meter. If we exclude this cycle, we have a **0.23 cm RMSE** and an **18.5 cm Average difference.** The results are excellent with these products. In the paragraph we will present the comparison between the Thematic hydro products and the FRM.

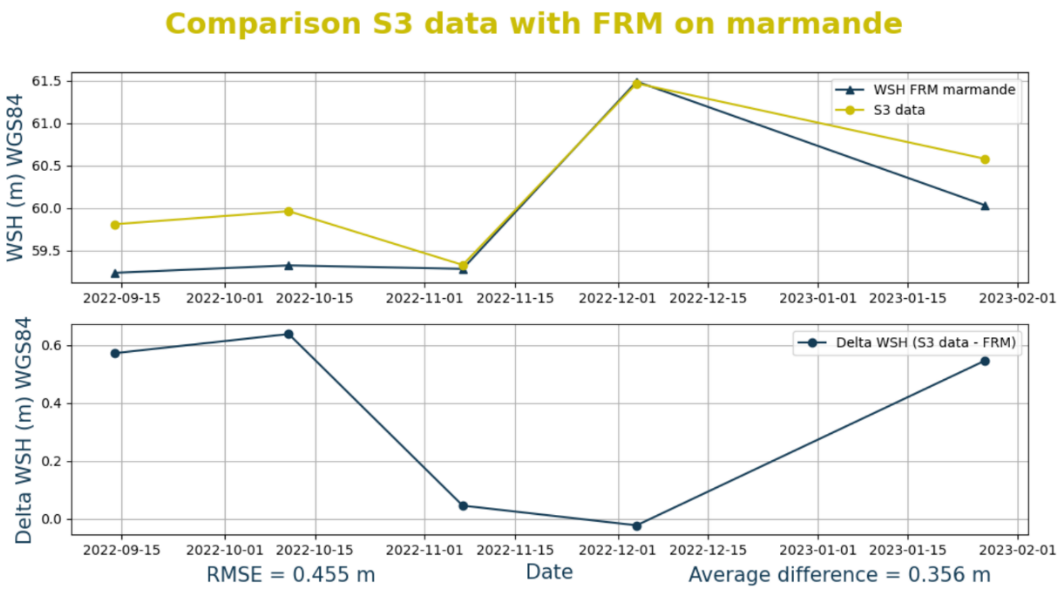


Figure 40: Comparison between FRM and Sentinel-3 measurements on the Marmande site for R.O.N.: 222 with thematic hydro products

The results with the hydro thematic products are mixed. First, only the R.O.N. 222 is available. The R.O.N. 299 is not available yet. We only proceed the comparison for the first virtual station. On this site, the results depend on the cycle. For 2 cycles the results are excellent with a difference under 3 centimetres. On the 3 other cycles the difference is around 60 centimetres. It seems that there is a bias on those cycles. Further investigations by the study of the radargrams must be performed to understand the difference of performance between the cycles.

3.2.3 Conclusion on the Marmande site

The Marmande site over the Garonne River represents a very interesting site as it has been identified as the highest complexity level defined in TD-6 [RD6] : Complexity Level 3. It means that the FRM must account for the river profile (topography of the river) and the propagation time between the water level recorded by the in-situ station and the time of the satellite measurement at the actual virtual station location. The Marmande site was also used as a R&D site to investigate the value of having the river profile at different river levels. The added value of such measurement is crucial on such complexity level site combined with the high dynamic of the Garonne River. **The river profile must be measured at, at least, 3 different water levels in order to account for the river dynamic in such sites.**

The propagation time correction allows to mitigate the impact of having an in-situ sensor not located below the Sentinel-3 track. The Marmande site is relevant to be used as an FRM site with RMSE of 42cm, 36 cm, 23 cm and 17.5 cm on the 3 respective virtual stations compared to the standard Sentinel-3 L2 products. The associated bias is respectively 32 cm, 8 cm, 18 cm and -4 cm. These results demonstrate the capability of the processing proposed in the TD-6 [RD6] to provide valuable FRM even in the case of high complexity sites. This site should be maintained in the future in order to meet the long-term requirement of the MPC.

4 The Maroni River

4.1 Campaign performed on the site

Two super sites were considered in the Maroni River basin, namely the “Chez Tooy” site (on the downstream part of the Maroni River) and the “Kio Konde” site, on the Tapanahoni River, left margin tributary of the Maroni. As mentioned in the TD-6 [RD6], the Maroni River basin and those two sites are particularly interesting because of characteristics such as their geographic context (deep Amazonian Forest with unease access and few to no human structures) or their geomorphologic features (rivers with complex bed profiles). The first site features a crossing between two Sentinel-3A and Sentinel-3B ground tracks in an area with very low slope close to the estuary, while the second is right under a Sentinel-3B ground track and features a break in the water line varying with the season and the water level.

On these sites, several campaigns were performed and permitted measuring with high accuracy the water profile along the rivers.

For “Chez Tooy” site, the bottom pressure sensor was levelled using the several passes with the GNSS carpet CalNaGeo and concurring dates. These deployments led to an ellipsoidal height of sensor’s zero of **-33,200 m**. That corresponds to an altitude of **0.010 m** after converting into **EGM08**. An extract of 2022 measurement of water level with CalNaGeo around the “Chez Tooy” site is provided hereafter in Figure 43.

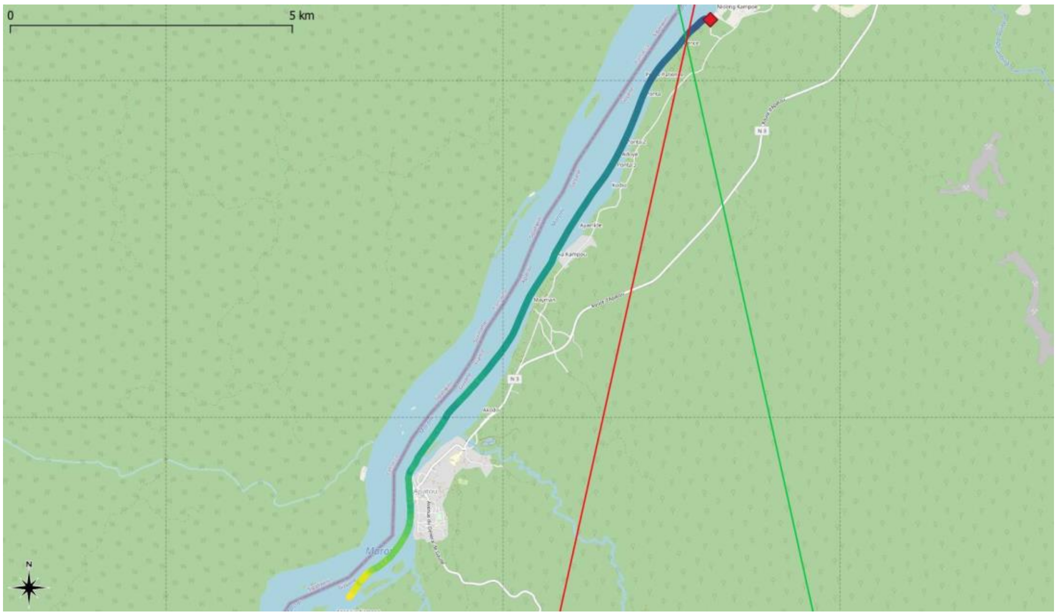


Figure 41: Ellipsoidal profile measured by CalNaGeo during the 2022 campaign on “Chez Tooy” site

For “Kio Konde” site, we used again the GNSS carpet (solely in 2022) measurement together with the in-situ station data to compute the levelling of the station. This gives an ellipsoidal height of the zero at **15.377 m**, i.e. an altitude of **48.467 m in EGM08**. Figure 42 provides the ellipsoidal profile of the reach near to the Kio Konde site as sampled by CalNaGeo on 12/07/2022.

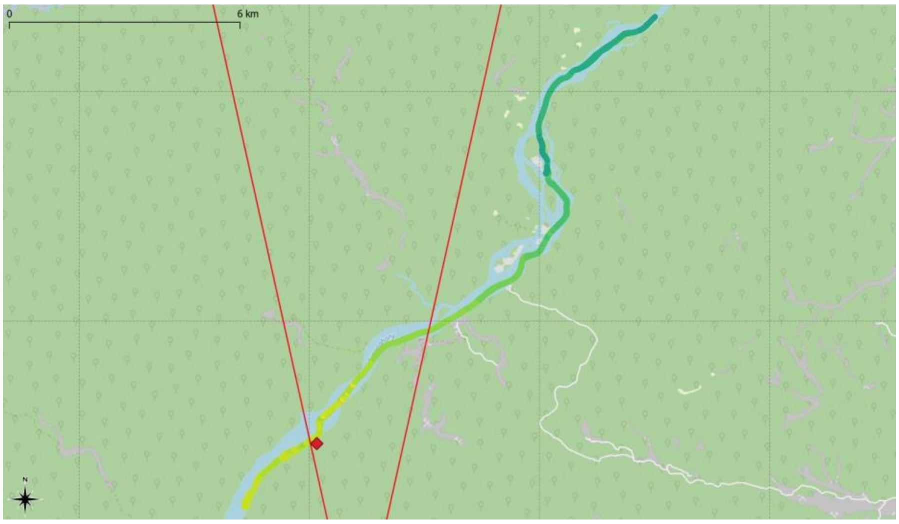


Figure 42: Ellipsoidal profile measured by CalNaGeo during the 2022 campaign on "Kio Konde" site

On Figure 43, the time series of water level as sampled by the in-situ station installed and operated by SCHAPI/DGTM is provided.

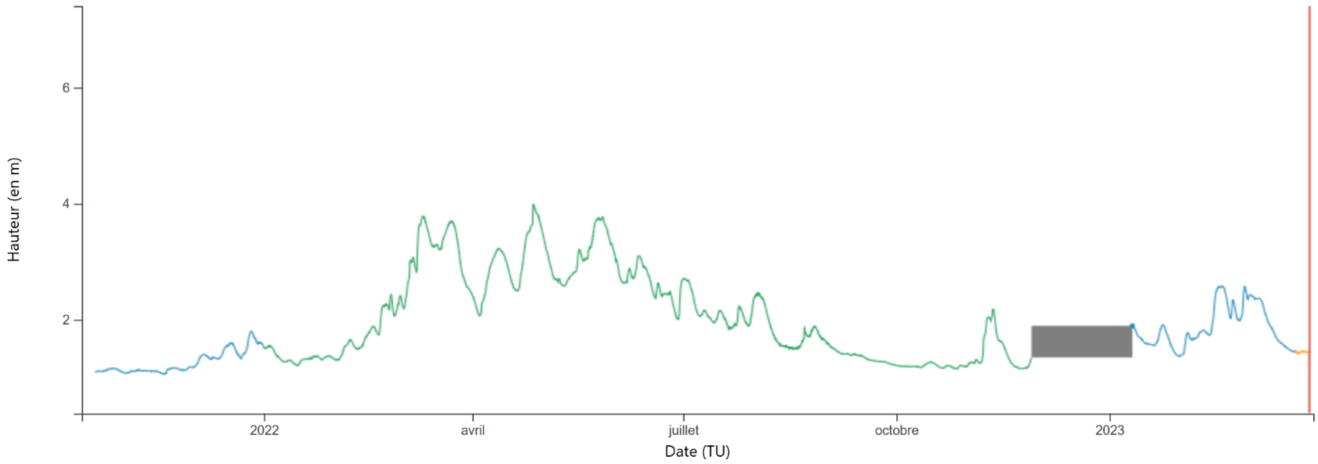


Figure 43: Time series of water level measured by in-situ sensor located in "Kio Konde", blue and green are pre-validated and validated data, orange are corrected data and red are raw data

4.2 Computing FRM on the Maroni River

4.2.1 Computing the FRM

On the Maroni River, there are 2 different "super sites", with rather different characteristics for each one. Following the Cal/Val site classification detailed in part the TD-6 document (RoadMap) [RD6], one can be considered as complexity level 0, and the other one complexity level 3 (due to slope variation with time). However, the considered rivers can have fast variations in water level, for both sites, we were able to install in-situ sensors right under the S3 ground track. Hence, this complexity level is 0 for "Chez Tooy" site and 3 for "Kio Konde".

Complexity level 0 site:

As mentioned before the “Chez Tooy” super-site corresponds to a complexity level 0 site for Sentinel-3B. The in-situ sensor is installed just under the satellite ground track. The computation of the FRM is very simple: there is no slope to be accounted for, no other in-situ data required. Yet, the measurement of the in-situ sensor must be performed at the exact same time as the satellite passes, which is not exactly the current configuration but can be set in a near future. Under this condition, the FRM simply corresponds to the measurement of the bottom pressure sensor. The Equation of the FRM on this site is:

$$\boldsymbol{WSH_{FRM}(t) \; = \; WSH_{IS}(t)}$$

Complexity level 3 sites:

As mentioned before the “Kio Konde” site corresponds to complexity level 3 sites. While the in-situ sensor is installed just under the satellite ground track, the variation of the true satellite pass from its theoretical ground-track may cause undesired effect due to local slope variations. This is illustrated on Figure 44. Indeed, the overpass can be whether upstream the break or downstream. In this case, while no compensation of time is needed, the slope should be considered. The FRM corresponds to the measurement of the in-situ sensor at the same time as the satellite corrected from the slopes measured by the moving sensor. The Equation of the FRMs on this site is:

$$\boldsymbol{WSH_{FRM}(t) \; = \; WSH_{IS}(t) + \left(\Delta WSH_{slope} \; - Corr_{evo\_tempo}\right)}$$

with $\boldsymbol{\Delta WSH_{slope} \; = \; WSH_{moving\_sensor\_at\_SGT} - WSH_{moving\_sensor\_at\_IS}}$

and where $\boldsymbol{WSH_{moving\_sensor\_at\_IS}}$ corresponds to the moving sensor measurement next to the in-situ sensor and

$\boldsymbol{WSH_{moving\_sensor\_at\_SGT}}$ to the moving sensor measurement at the actual position of the satellite ground track. $\boldsymbol{Corr_{evo\_tempo}}$ corresponds to the correction related to the spatial and temporal evolution that we apply on the moving sensor measurements to correct the water level evolution of the river during the campaign time.

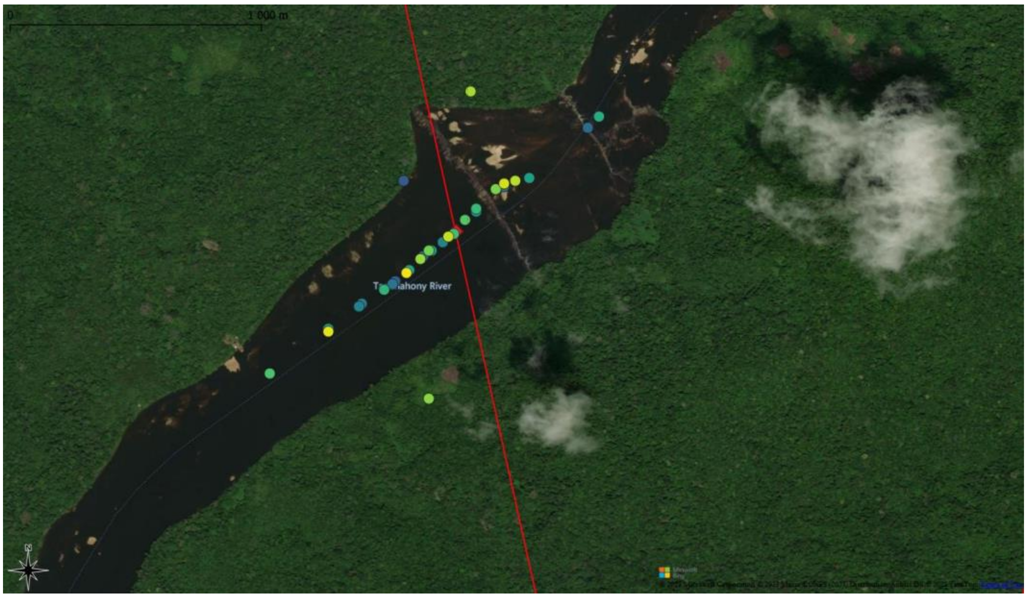


Figure 44: Excursion of the Sentinel-3A on the “Kio Konde” super site

4.2.2 Comparison with Sentinel-3

This exercise has been performed here by Hydro Matters team. The FRM is computed as described in the TD-6 document [RD6]. First, we will present the results on “Chez Tooy” super site and then we will present the results on “Kio Konde” super site.

Results on “Chez Tooy” super site:

The team performed the comparison with the water level measurements from Sentinel-3A on the downstream part of the super site. Due to the destruction of the dock during exceptional flood in 2020, we only had two years for comparison. However, this permitted sampling both high and low water conditions. The comparison is provided on Figure 45. Figure 45 also provides the comparison with raw data that we processed using a physical retracker, and not the OCOG processing made in Hydroweb.

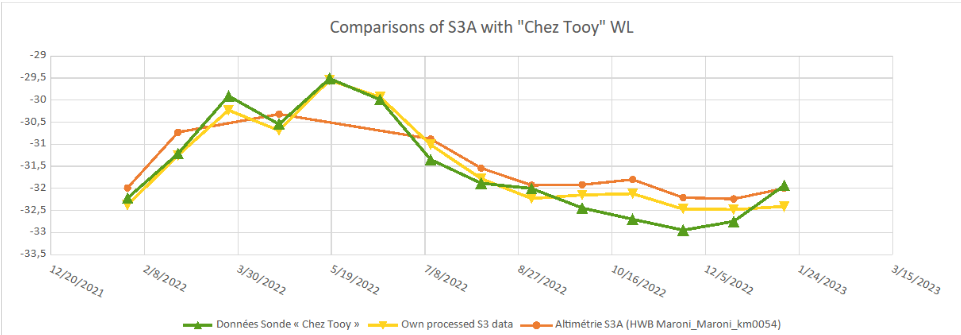


Figure 45: Comparison of the water level measured by in-situ sensors installed on “Chez Tooy” super site with Sentinel-3A measurements

This comparison led to a rather acceptable **RMS of 0.420 m**, and mean difference of **–0.353 m**, for S3 OCOG from Hydroweb. When correcting from this bias, the **RMS** between the in-situ observation and altimetry drops to **0.226 m**. For the data that we processed besides, **RMS and mean difference were of 0.302 m and 0.051 m**. It is worth noting that the time sampling of the bottom pressure sensor (half an hour) may not be totally adequate, as ocean tide processes can cause variation of centimetres in tens of minutes. If considering only high waters, out of ocean tide influence, the comparison is much better, with mostly a bias.

Results on “Kio Konde” super site:

On this site, the analysis was made more difficult by the presence of the break in river profile. Figure 46 provides the comparison between water level from in-situ, from OCOG retracker taken from Hydroweb and from our own physical retracker. It is clearly evidenced here that a time variable estimation of slope would benefit to calculate the FRM, instead of not correcting or using the slope we were able to obtain from GNSS survey.

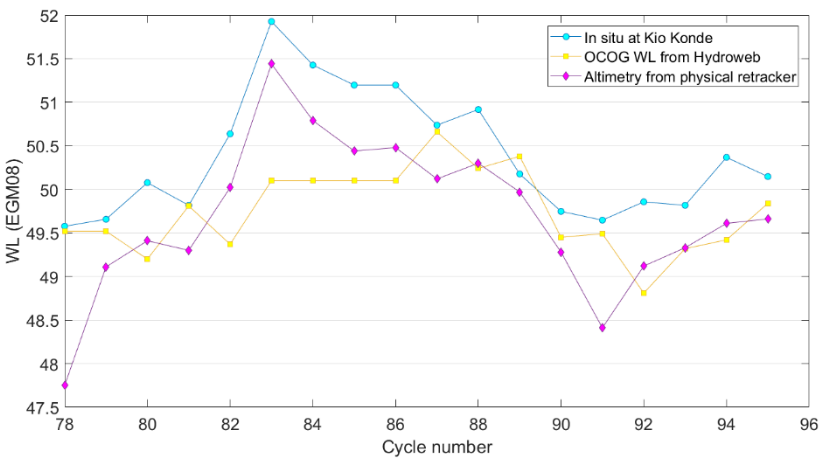


Figure 46:Comparison between in-situ measurement with Sentinel-3A measurements with 2 different retracker

The comparison led to **mean differences** of **0.638 m and 0.688** m respectively for the series from Hydroweb and from the physical retracker, leading to **RMS** values after removal of these differences of **0.556 m and 0.347 m** respectively.

4.2.3 Conclusion on the Maroni site

On “Chez Tooy” site, we concluded that the location is very valuable for FRM, as it does not need any adjustment further than reconfiguring the sensor.

On “Kio Konde” site, the local slope variation, and its impact on varying pass location of the satellite makes the site more difficult to implement, with the necessity of inferring the local slope for compensating the actual pass location. However, this can be done quite easily using one of the moving sensors experimented during this project.

In order to meet the long-term requirements, this site should be maintained in the future. This site is also a good demonstrator for federating the local community.

5 The Rhine River (French part)

5.1 Campaign performed on the site

5.1.1 In-Situ sensors

On the Rhine River we performed a campaign to install 6 in-situ sensors on 5 different "super sites": "Erstein", "Strasbourg", "Chalampé", "Ottmarsheim" and "Gerstheim". The area near the Rhine in France is very interesting because there is a complete network of canals and small water reservoir. The main canal is "Le Grand Canal d'Alsace", parallel to the Rhine River, named "Old Rhine". On this canal there are a lot of dams to control the discharge. Sentinel-3A, Sentinel-3B and Sentinel-6 ground tracks crosses the Rhine River near the locations where we installed the Micro-Stations. These sites have been chosen because the Rhine River and the "Grand Canal d'Alsace" are canalized waterbodies controlled by successive dams. The geometry is also very interesting because the Rhine River is collinear with Sentinel-3A and Sentinel-3B ground tracks. This geometry is only present in the Rhine River super sites. They are ideal cases to evaluate the best possible performances that can be achieved by Sentinel-3 with this geometry. All the stations are not installed on the same waterbody. Further explanations on the choice of these sites are given in the TD-6 document [RD6]. The full campaign is described in the corresponding campaign logs [RD11], [RD16] . The first 3 stations have been installed on the 06/04/2022, the second installation campaign was on the 11/08/2022 and finally the 2 last stations have been installed on the 26/08/2022. All the time-series are available since these dates.

The first step of the data analysis is the computation of the reference height of the Micro-Station from the GNSS measurements recorded by the Septentrio base. This procedure is described in the TD-12 document [RD11],[RD16]. We performed a GNSS measurement on each site. In the next paragraph we will present the results of the positioning of all the Micro-Stations and a short analysis of the data acquired since the installation.

Erstein:

In Erstein we installed 2 Micro-Stations under a Sentinel-6 ground track. The stations are installed on the same structure, one on each side of a dam. The aim of this super-site is to improve the knowledge of altimetric measurements when the satellite overflies a dam. This configuration is present in the other super sites in the Rhine River. The knowledge acquired on this site will be helpful for the other sites. The 2 Micro-Stations are fixed on the same structure at the same altitude. We only performed one precise altimetric reference for both Micro-Stations. The PPP positioning of the base provides excellent results with a median height of **209.759 m (WGS84)** with a standard deviation of **2 cm**. During this GNSS measurement the base tracked **17 satellites** in average. The quality of the GNSS measurement is excellent. The rope access technicians have measured a vertical distance between the Micro-Station and the centre of phase of the GNSS base of **2.64 m**. It results in a reference height for the Micro-Station of **207.119 m** in ellipsoidal height, that corresponds to an altitude of **159.171m (IGN69)** after applying the French geoid.

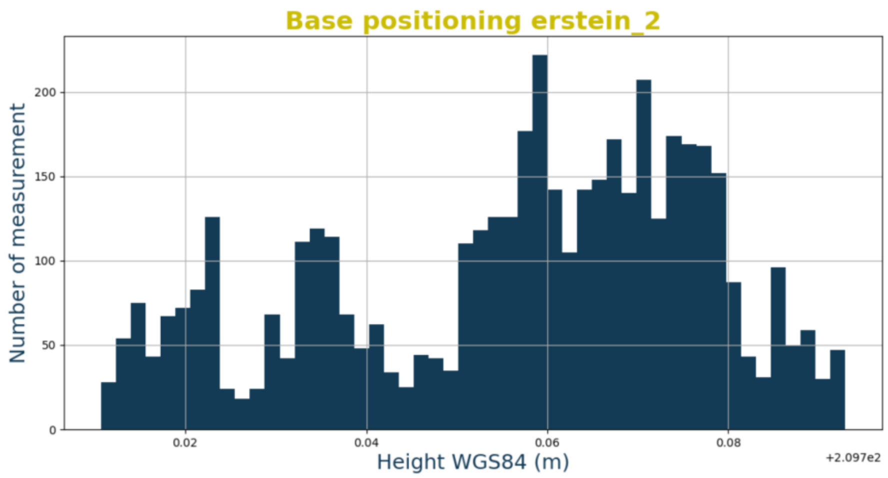


Figure 47: Histogram of the altitudes of the base computed by PPP for "Erstein_2"

The combination of this GNSS processing and the LiDAR measurements provides the precise altitude of the water measured by the Micro-Station. We obtain the time-series measured by the Micro-Station "Erstein_1" (Figure 48) and the time series measured by the Micro-Station "Erstein_2" (Figure 49).

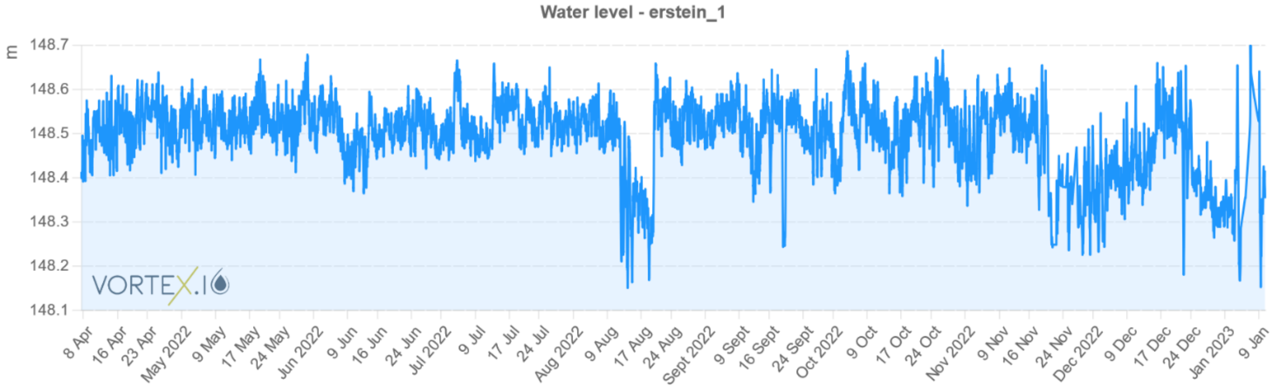


Figure 48: Time series of water surface height measured by the station labelled "erstein_1" since the installation

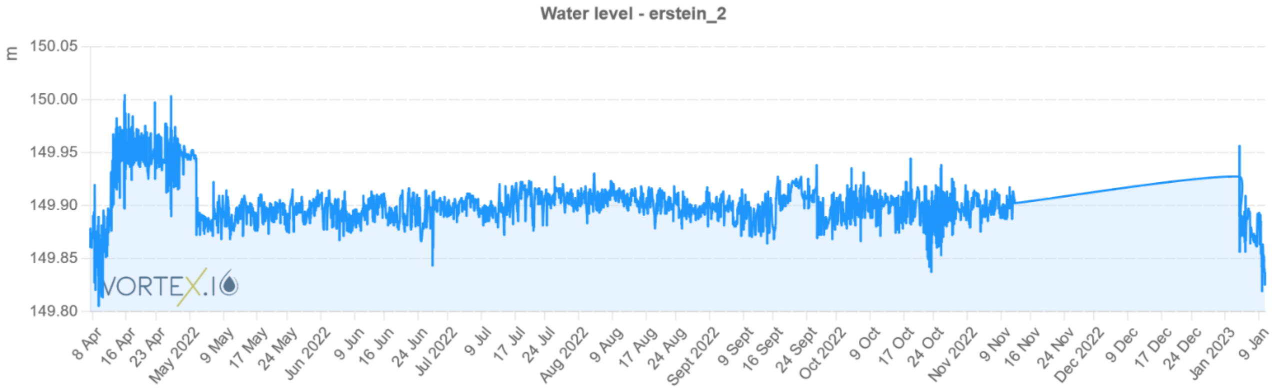


Figure 49: Time series of water surface height measured by the station labelled "erstein_2" since the installation

The measurements of both Micro-Stations are very stable as expected. The sensors are installed on a dam that control the water level. The Micro-Station named "erstein_1" is installed downstream just after the waterfall. We can see that its measurements are noisier than the ones made by "erstein_2". The water is turbulent after the waterfall, it is logic to have noisier measurements than upstream. On "erstein_2" we can see a rise of the water level during 2 weeks in April and then a sudden drop of the water level. This is due to the accumulation of floating wood. There is a data gap in the time-series measured by "erstein_2". This gap is due to a hardware failure of the Micro-Station. We changed the Micro-Station in January.

Strasbourg:

The PPP positioning of the base provides good results with a median height of **198.182 m (WGS84)** and a standard deviation of **5.5 cm**. During this GNSS measurement the base tracked **13 satellites** in average. Even with this standard deviation we have a good confidence in the positioning. The high standard deviation comes from a punctual external perturbation. The rest of the time series is very stable around the median height. The rope access technicians have measured a vertical distance between the Micro-Station and the centre of phase of the GNSS base of **0.505 m**. It results in a reference height for the Micro-Station of **197.677 m** in ellipsoidal height, that corresponds to an altitude of **149.873 m (IGN69)** after applying the French geoid.

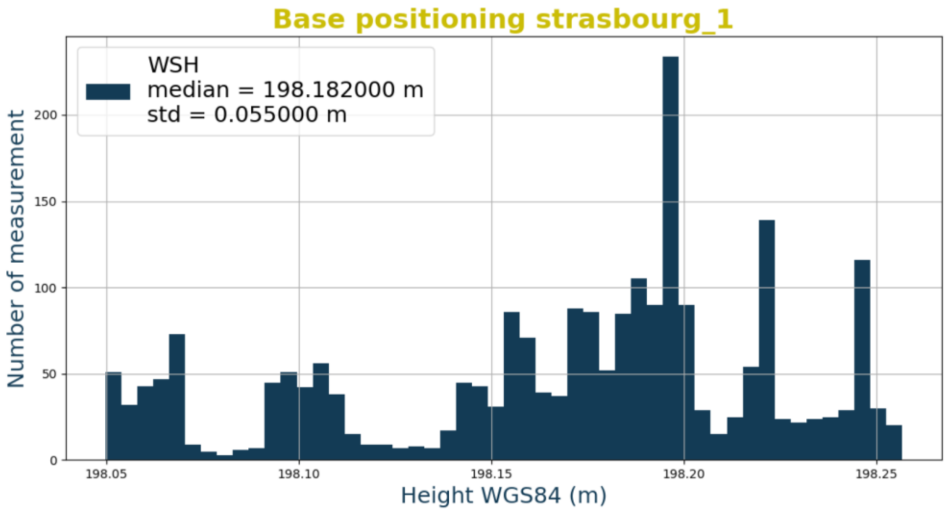


Figure 50: Histogram of the altitudes of the base computed by PPP for "strasbourg_1"

The combination of this GNSS processing and the LiDAR measurements provides the precise altitude of the water measured by the Micro-Station. We obtain the time-series measured by the Micro-Station "Strasbourg_1" (Figure 51)

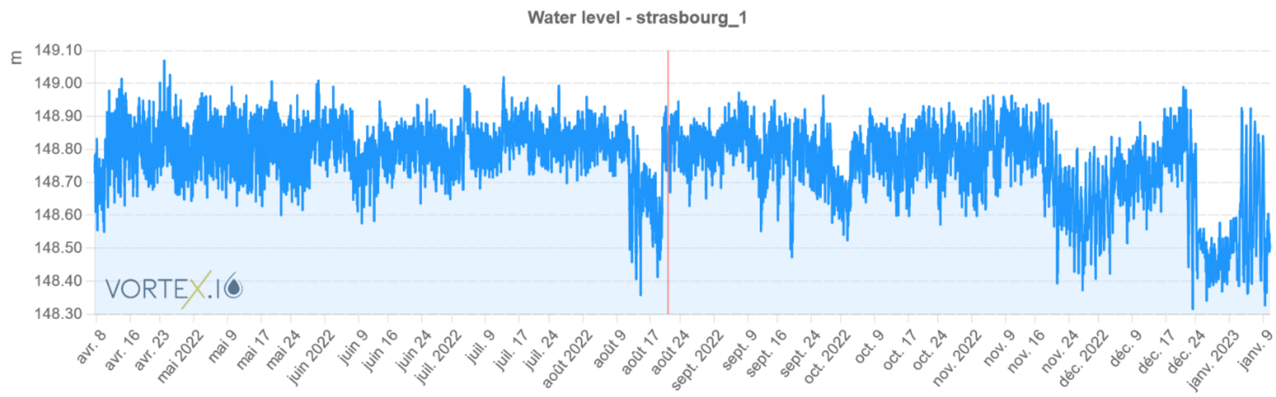


Figure 51: Time series of water surface height measured by the station labelled "strasbourg_1" since the installation

The data measured in by "Strasbourg_1" are very stable. The Micro-Station is installed on "Le Grand Canal d'Alsace", a controlled waterbody. The measurements are noisy. We explain this noise by the river traffic. "Le Grand Canal d'Alsace" is one of the main River in Europe in terms of river traffic. The station is installed on a pontoon on the canal. When a boat passes next to the station, it generates turbulences that impact the measurements.

Gerstheim:

The PPP positioning of the base provides excellent results with a median height of **201.924m (WGS84)** with a standard deviation of **1.3 cm**. During this GNSS measurement the base tracked **12 satellites** in average. The quality of the GNSS measurement is excellent. The rope access technicians have measured a vertical distance between the Micro-Station and the centre of phase of the GNSS base of **-0.43m**. It results in a reference height for the Micro-Station of **201.967 m** in ellipsoidal height, that correspond to an altitude of **153.922 m (IGN69)** after applying the French geoid.

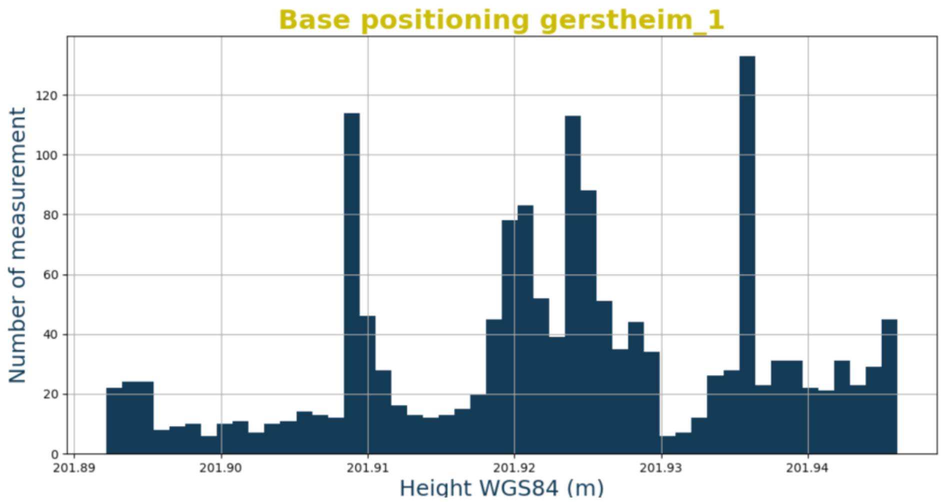


Figure 52: Histogram of the altitudes of the base computed by PPP for "gerstheim_1"

The combination of this GNSS processing and the LiDAR measurements provides the precise altitude of the water measured by the Micro-Station. We obtain the time-series measured by the Micro-Station "gerstheim_1" (Figure 53).

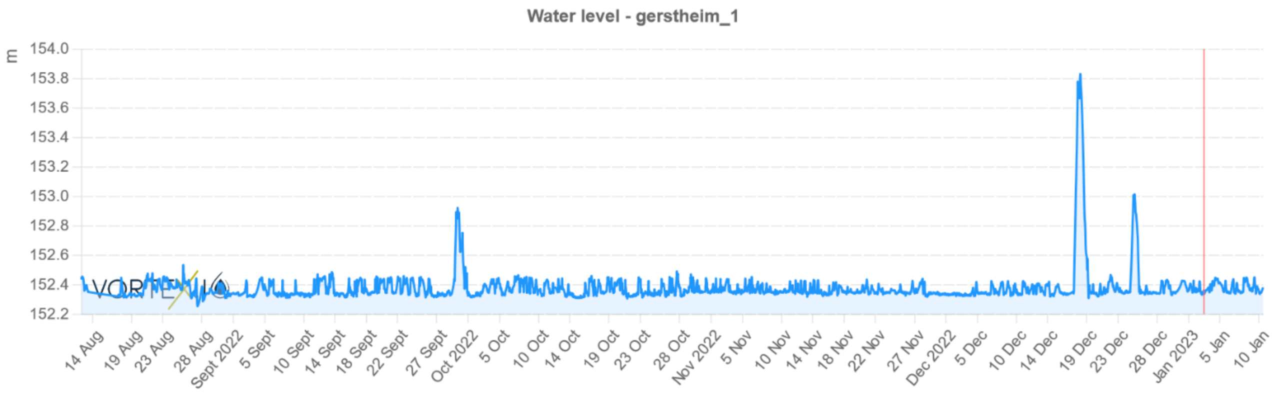


Figure 53: Time series of water surface height measured by the station labelled "gerstheim_1" since the installation

We observe on this station a similar result: the water level measured by the station is very stable. This station is installed on the "Old Rhine". This part of the Rhine is canalized and is used by the maintainer of the canals network to regulate the water level of the other canals. The average level is controlled and do not change during the year. We can observe 3 flood events. These events can only be seen in the "Old Rhine" for the reason mentioned before. We have precise measurements with this station.

Chalampé:

The PPP positioning of the base provides good results with a median height of **274.097 m (WGS84)** and a standard deviation of **3.8 cm**. During this GNSS measurement the base tracked **9 satellites** in average. Even with this standard deviation we have a good confidence in the positioning. The high standard deviation comes from noise, but the rolling mean of the position is very stable around the median during all the recording time. The rope access technicians have measured a vertical distance between the Micro-Station and the centre of phase of the GNSS base of **0.512 m**. It results in a reference height for the Micro-Station of **273.585 m** in ellipsoidal height, that corresponds to an altitude of **224.982 m (IGN69)** after applying the French geoid.

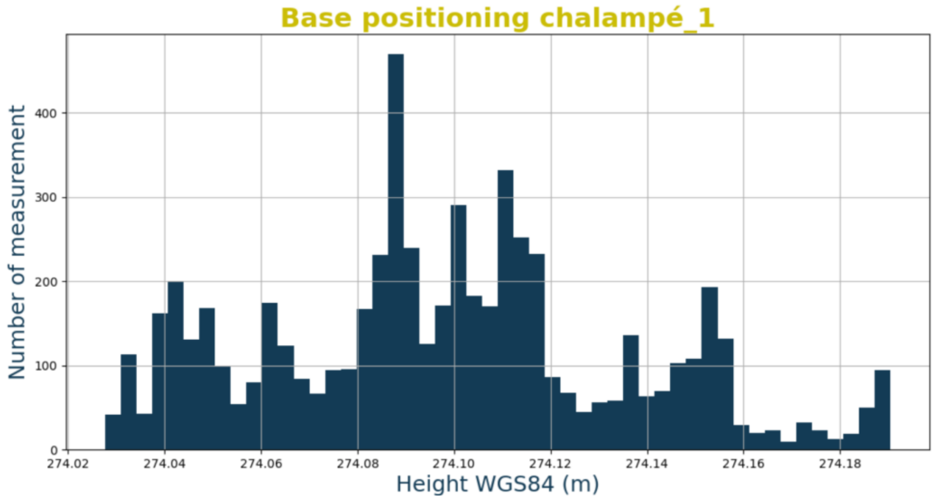


Figure 54: Histogram of the altitudes of the base computed by PPP for "chalampé_1"

The combination of this GNSS processing and the LiDAR measurements provides the precise altitude of the water measured by the Micro-Station. We obtain the time-series measured by the Micro-Station "chalampé_1" (Figure 55)

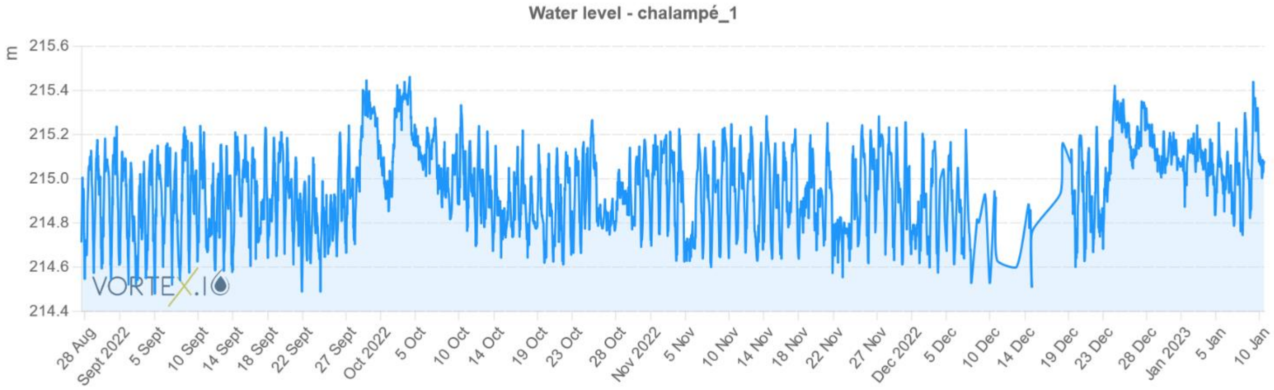


Figure 55: Time series of water surface height measured by the station labelled "chalampé_1" since the installation

The data measured by "chalampé_1" is very stable. As "Strasbourg_1", the Micro-Station is installed on "Le Grand Canal d'Alsace". We observe a daily evolution in the water level. The daily oscillations have an amplitude around 50 centimetres. We assume that these oscillations are generated by the hydrological control of the waterbody.

Ottmarsheim:

The PPP positioning of the base provides good results with a median height of **273.913m (WGS84)** and a standard deviation of **3.6 cm**. During this GNSS measurement the base tracked **10 satellites** in average. Even with this standard deviation we have a good confidence in the positioning. As for "Chalampé_1", the high standard deviation comes from noise, but the rolling mean of the position is very stable around the median during all the recording time. The rope access technicians have measured a vertical distance between the Micro-Station and the centre of phase of the GNSS base of **0.565 m**. It results in a reference height for the Micro-Station of **273.348 m** in ellipsoidal height, that corresponds to an altitude of **224.741 m (IGN69)** after applying the French geoid.

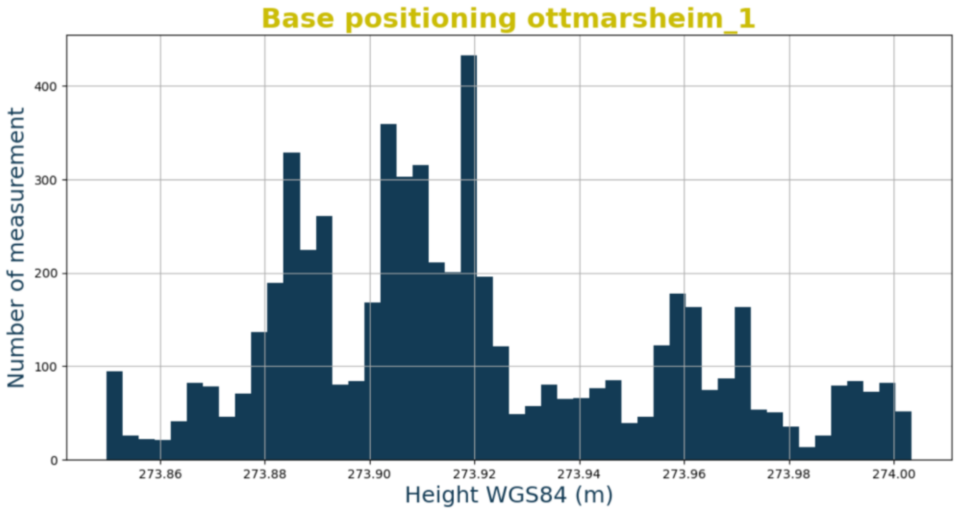


Figure 56: Histogram of the altitudes of the base computed by PPP for “ottmarsheim_1”

The combination of this GNSS processing and the LiDAR measurements provides the precise altitude of the water measured by the Micro-Station. We obtain the time-series measured by the Micro-Station “ottmarsheim_1” (Figure 57)

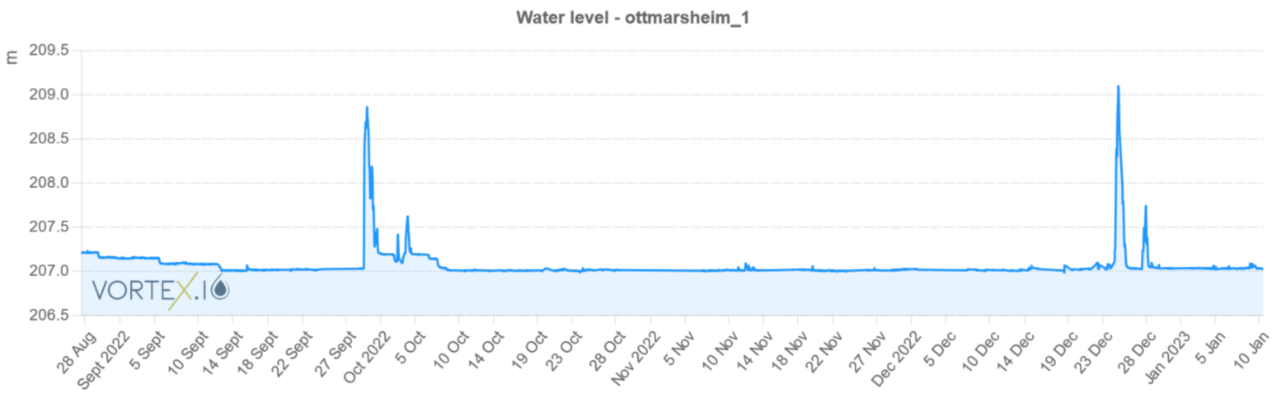


Figure 57: Time series of water surface height measured by the station labelled "ottmarsheim_1" since the installation

We observe a similar result for this station: the water level measured by the station is very stable. The water level measured by this station is comparable with the one measured by “gerstheim_1”. This station is installed on the “Old Rhine”. The average level is controlled and do not change during the year. This station observes the same flood events as “Gerstheim_1” during fall.

5.1.2 Moving Sensor

As mentioned before, the satellite ground tracks don’t exactly overfly the Micro-Stations installed in the frame of the project in the super sites “Ottmarsheim”, “Gambsheim” and “Chalampé”. On these 3 sites we need a slope measurement to compute a FRM under the satellite ground tracks. A campaign has been performed to fulfil this objective. We do not need more campaign because the Rhine River is a steady canalized waterbody, and a single slope measurement will be enough to have a good slope measurement at every water level. The campaign is divided into 2 parts: “Gambsheim” and “Ottmarsheim”/”Chalampé”. The distance between the 2 sites is around 100 kilometres. It is not possible to use the same GNSS base measurements to perform the PPK positioning of the altimeter on the 2 sites. On the second site, we will perform measurements on the “Old Rhine” and on the “Grand Canal d’Alsace”, that correspond respectively to the “Ottmarsheim” and “Chalampé” supersites. The campaign is fully described in the corresponding campaign logs [RD19].

In the next paragraph we present the results of the campaign performed by the vorteX.io team in partnership with a drone pilot company I-TECHDRONE. We will present the results on all the different sites at the same time. As for the Micro-Stations, the first data analysis we’ll present is the positioning of the geodesic base and the positioning of the altimeter. Then we present the results of the data analysis of the LiDAR measurements. The procedure applied during this campaign is described in the corresponding campaign logs [RD19].

The position of the bases is obtained by performing a PPP (Precise Point Positioning) processing. The obtained position of the base is very precise on both sites, with a standard deviation lower than **3 mm**, as shown in Figure 58. The number of satellites tracked by the GNSS base during the acquisition time is around **18** in average. The satellites of the GALILEO, GPS and GLONASS constellations are used to perform the positioning. The quality of the positioning is very good. The base position is **185.9 m (WGS84)** in Gambsheim and **272.402 m (WGS84)** in “Ottmarsheim”/“Chalampé”.

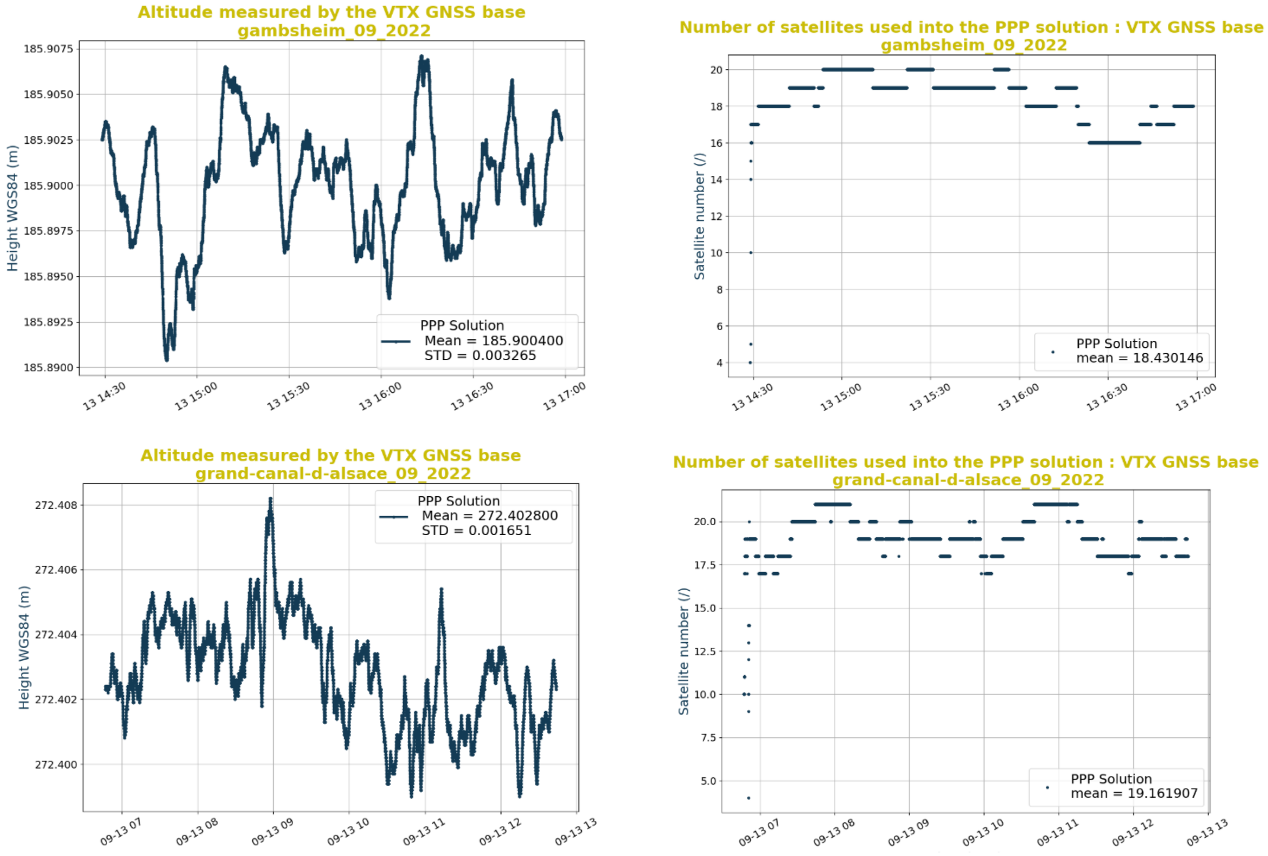


Figure 58: PPP positioning of the base on the left and the number of satellites tracked by the base on the right in Gambsheim on the top and in Chalampé/Ottmarsheim on the bottom

Once the precise position of the base is computed, we can perform the PPK positioning of the altimeter for all the flights. All the ambiguities are fixed when the altimeter is flying and thus the positioning is of good quality. We can see in Figure 59 the evolution of the altimeter altitude during the first flight of the campaign in “Gambsheim”. This precise positioning allows to get a precise water surface height measurement.

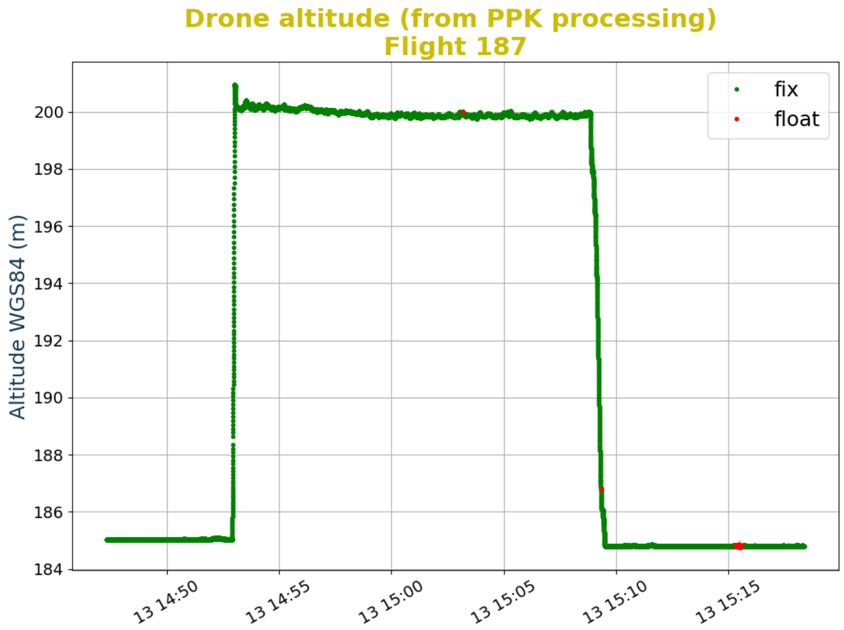


Figure 59: Altitude of the altimeter during the first flight in Gambsheim

Once the precise positioning computed, we can compute the water surface height from LiDAR measurements. We have applied a running mean (window of 15 seconds) on the WSH measured by the altimeter to decrease the measurement noise. The LiDAR measurements are performed at 7 Hz, and we finally resampled to 0.5 Hz for the data dissemination.

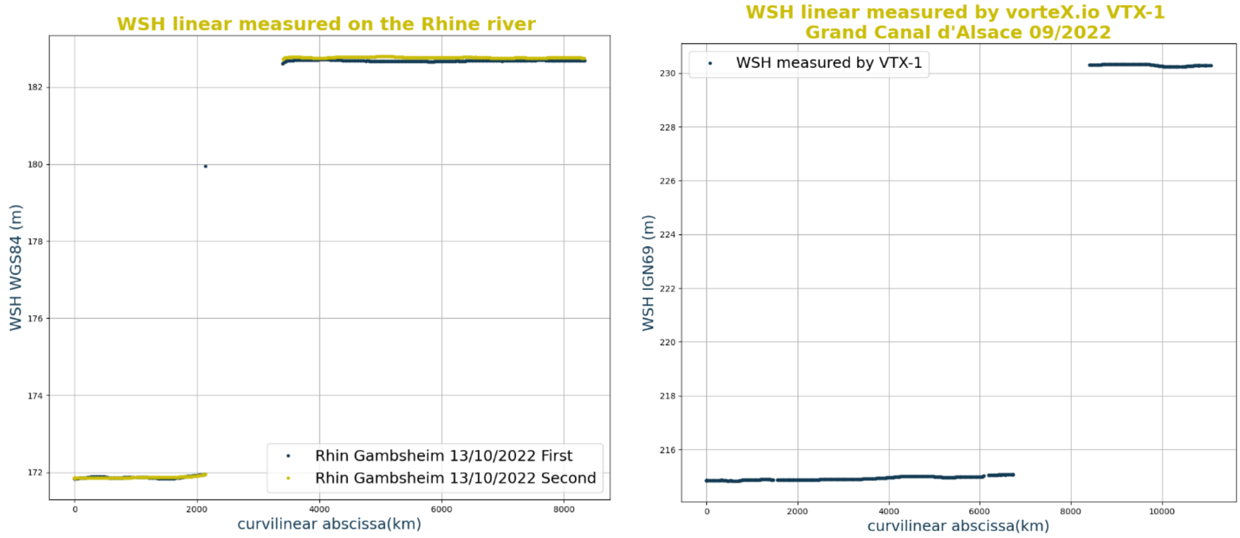


Figure 60: Water surface height profile measured by vorteX.io light altimeter during the campaign, in Gambsheim on the left and in Chalampé on the right

The results of this campaign are excellent on the Gambsheim and Chalampé super sites. The water topography measurements are very precise. On both sites the drone measurements have been performed on both sides of a dam. We can observe on the linear the difference in altitude between the 2 sides of the dam. These linear have not been corrected from the water evolution of the Rhine River because of a lack of in-situ data. We planned to use EDF in-situ sensors to correct the water level evolution because there are not vorteX.io micro-station on each side of the dam. Unfortunately, the quality of the EDF data is very poor. We have no confidence in the measurement they provided us. The doubts we had were confirmed by the comparison with the vorteX.io measurements in “Chalampé”. The absence of this correction is not a problem on the “Rhine River” super sites because it is a canalized river with no strong dynamic.

In other sites as in Marmande, this would have been an issue. This problem enlightens the fact that we should not rely on external in-situ sensors.

The topography measurements on the “Old Rhine” for the “Ottmarsheim” super site have not been performed during this campaign. The comparison will still be performed with Sentinel-3B measurements with a slope estimation computed from in-situ data. Full details on the campaign performed on “Ottmarsheim” super-site are described in the corresponding TD-12 [RD19].

5.2 Computing FRM on the Rhine River

5.2.1 Computing the FRM

On the French part of the Rhine River there are 4 different “super sites”, each site has different characteristics. Following the Cal/Val site classification detailed in part the TD-6 document (RoadMap) [RD6], 2 super-sites are complexity level 0 and 1, one site is complexity level 0 and 2. The Rhine River is located along the Sentinel-3 ground track, and with a slope topography measurement we can perform comparison at the location of the Micro-Station (Complexity level 0) or upstream/downstream (complexity level 1 or 2 depending on the waterbody dynamic). The last site, “Gambsheim” corresponds to a complexity level 1 for both Sentinel-3B and Sentinel-3A.

<u>Complexity level 0 site:</u>

As mentioned before the “Ottmarsheim”, “Strasbourg” and “Gerstheim” super-sites correspond to complexity level 0 sites. The in-situ sensor is installed just under the satellite ground track. The computation of the FRM is very simple: there is no slope to be accounted for, no other in-situ data required, the measurement of the in-situ sensor can be performed at the exact same time as the satellite passes. The FRM simply corresponds to the measurement of the vorteX.io Micro-Station that has been configured to perform a measurement at the exact time of the Sentinel-3B pass for the ground track #158. The Equation of the FRM on this site is:

$$\boldsymbol{WSH_{FRM}(t) \; = \; WSH_{IS}(t)}$$

<u>Complexity level 1 sites:</u>

As explained before, due to the geometry of the Rhine River, two of the complexity “level 0” sites are also complexity “level 1” sites. The “Gambsheim” site is only complexity “level 1”. Thanks to the installation of the instrumentation described in the previous paragraph: a vorteX.io Micro-Station and slope measurements, and following the recommendations related to this site class, we can compute the FRM measurement and then compare to Sentinel-3 data.

As mentioned before these sites correspond to complexity level 1 sites. The in-situ sensors are not installed just under the satellite ground tracks. The computation of the FRM is very simple: The measurement of the in-situ sensors can be performed at the exact same time as the satellite passes and the slope must be accounted for. The slope is measured by moving sensors on some sites and with ICESAT2 on other sites. The FRM corresponds to the measurements of the vorteX.io Micro-Stations that have been configured to perform a measurement at the exact time of the Sentinel-3 and this measurement is then corrected by the slope. The Equation of the FRM on these sites is:

$$\boldsymbol{WSH_{FRM}(t) \; = \; WSH_{IS}(t) + Slope}$$

<u>Complexity level 2 site:</u>

The last site (“Ottmarsheim”) is a complexity level 0 and 2 site because the Rhine River is along the Sentinel-3 ground track but, on this section, we have measured a strong dynamic that must be accounted for. Thanks to the installation of the instrumentation described in the previous paragraph: a vorteX.io Micro-Station and slope measurement with a moving sensor, and following the recommendations related to this site class, we can compute the FRM measurement and then compare to Sentinel-3 data. The Micro-Station will perform its measurement at $\boldsymbol{t \; + \delta_t}$. The topography of the Rhine River must be accounted for. The FRM corresponds to the measurements of the vorteX.io Micro-Stations that have been configured to perform a measurement at the exact time $\boldsymbol{t \; + \delta_t}$ corrected by the slope measured by the moving sensors. The Equation of the FRM on these sites is:

$$\boldsymbol{WSH_{FRM}(t) \; = \; WSH_{IS}(t + \; \delta_t) + Slope}$$

Prerequisites:

On the three complexity level 0 “super sites” there are no prerequisites for the computation of the FRM. On the complexity level 1 and level 2 “super site” the prerequisites are presented in the next paragraph:

1. The centreline

For both complexity level 1 and 2 a river centreline is needed for the FRM processing on the “Rhine River” and “Grand Canal d’Alsace”. This centreline is computed from the TOPAGE database (French river database) or can be computed from a kml file built from a Google Earth trajectory. The centreline is the curvilinear abscissa along the river. The computed centrelines on both river for all the super sites are shown in Figure 61.

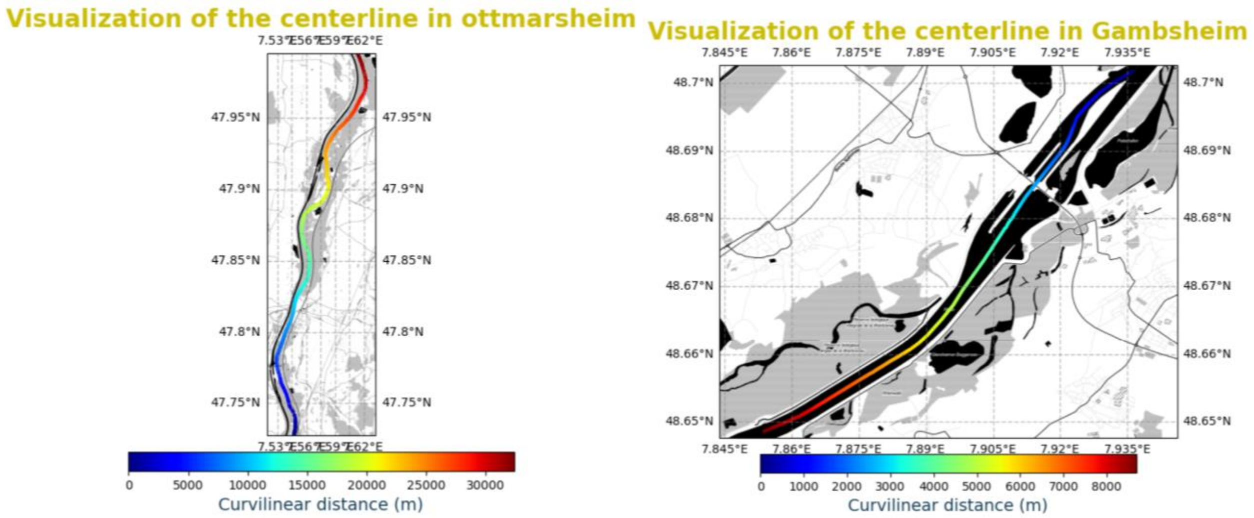


Figure 61: Visualisation of the centreline for the super sites in Alsace

2. River topography measurements

As mentioned in the classification of the super sites [RD6], on complexity level 1 and complexity level 2 super sites we need a slope measurement to compute the FRM. As mentioned before, a drone campaign has been performed on each site to measure the river profile. On “Ottmarsheim” super site, we will use an estimation of the slope from in-situ sensors or ICESAT-2 to compute the FRM.

5.2.2 Comparison with Sentinel-3

This exercise has been performed by SERTIT team. The FRM is computed as described in the TD-6 document [RD6]. In the next paragraph we will present the FRM processing performed for a complexity level 1 super site: “Chalampé”. The FRM processing for the complexity level 0 super sites is easier because there is no slope to be accounted for. So, the step 3 must be ignored and the final FRM is simply the measurement of the micro-station at the time ***t***.

FRM Processing:

1. Load Sentinel-3 data and get the actual time ***t*** and location of the satellite measurements.

Sentinel-3 data are downloaded from the ESA Copernicus Open Access Hub (https://scihub.copernicus.eu/). The Figure 62 illustrates data from cycle 70 on the S3B ground track #236.

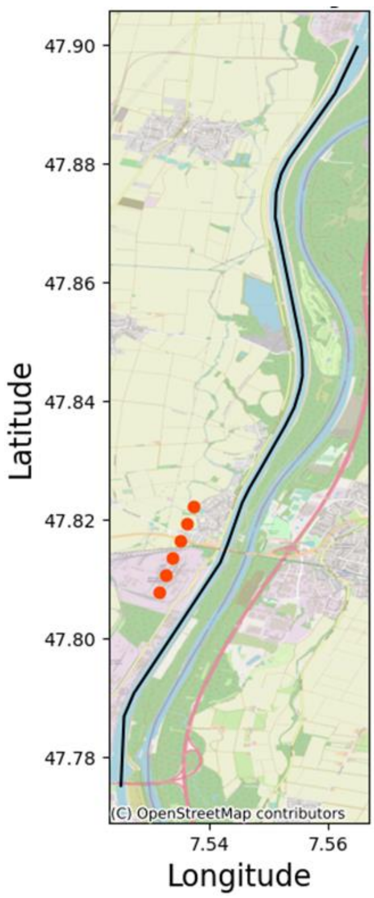


Figure 62: Map showing the positions of the S3B measurements on cycle 70 track #236 over the "Grand Canal d'Alsace"

2. Compute the height at the reference station at ***t***

The ellipsoidal height measured by "chalampé_1" Micro-Station at ***t*** is selected (or interpolated if the time does not correspond exactly, i.e. less than 1 minute).

3. Compute the slope correction from the drone profiles.

The slope correction corresponds to the **δh** between the drone height measured at the location of the Micro-Station "Chalmapé_1"' and the actual location of the Sentinel-3 measurement. The "Grand Canal d'Alsace" is a canalized waterbody so the linear measured by the drone at a certain water level is valid at every water level.

4. Finally, the FRM value is computed combining the height at the reference station at ***t*** and the slope correction.

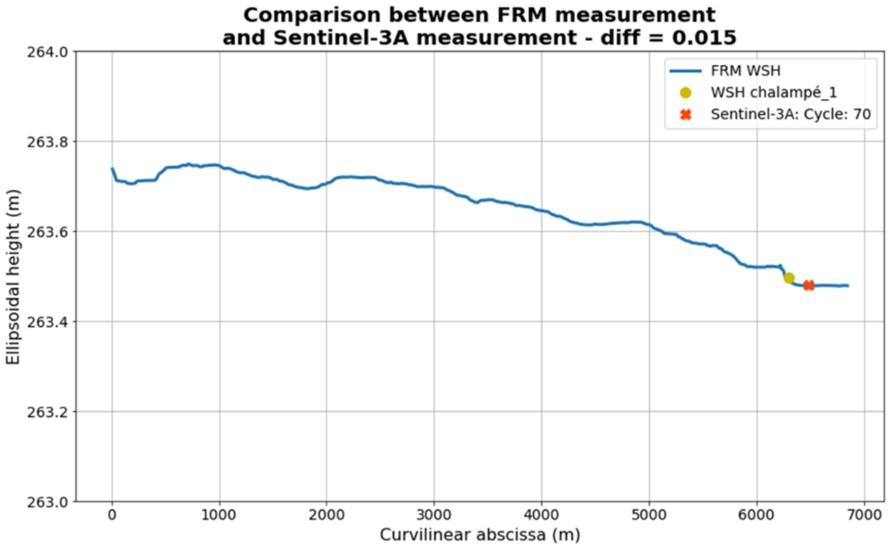


Figure 63: Comparison between the FRM in Chalampé and the Sentinel-3B measurement

The section of the Rhine studied is quite complex from a topological standpoint. The canalized Rhine and the old Rhine form two distinct branches separated by vegetation islands and presenting a difference in altitude up to 10m. During the data acquisition by Sentinel-3, the sensor sometimes targets one branch or the other, resulting in a difference of 6 to 10 meters. Furthermore, the satellite's path is parallel to the river, thus increasing the possibility of aiming upstream or downstream of the station.

The methodology applied to other rivers, consisting of retrieving the Sentinel-3 point closest to the FRM, results in completely erroneous measurements in the case of the Rhine because the Sentinel-3 measurement was performed either in the canal or in the old Rhine. The example of Ottmarsheim site is presented in the figure below.

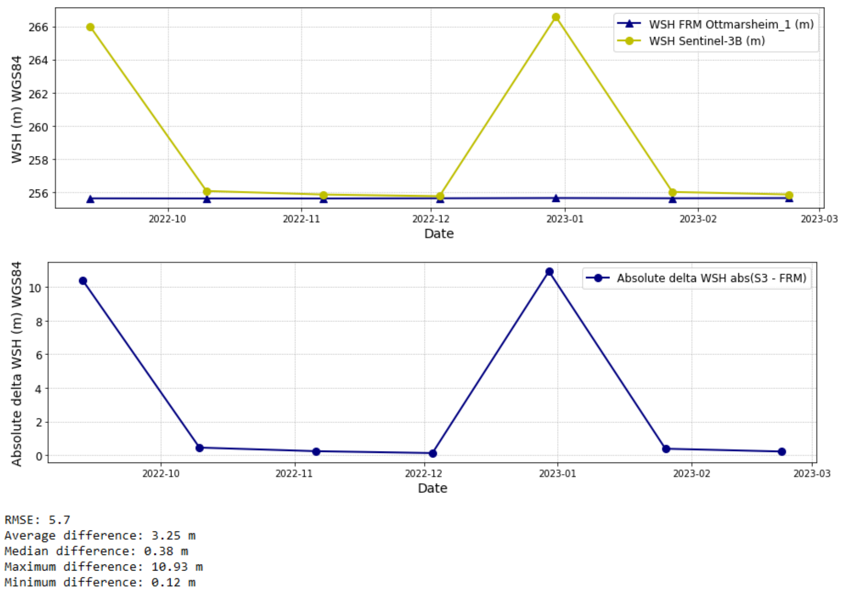


Figure 64: Time Series Analysis of Sentinel-3/FRM Comparison on Ottmarsheim site comparing the closest S3 point to the FRM station

Consequently, we have implemented an approach aimed at selecting the Sentinel-3 measurement that minimizes the difference with the FRM's water surface height. It may have occurred that during some cycles, no Sentinel-3 measurement was performed on the "correct" side of the Rhine, resulting in a significant discrepancy between the Sentinel-3 values and the in-situ station.

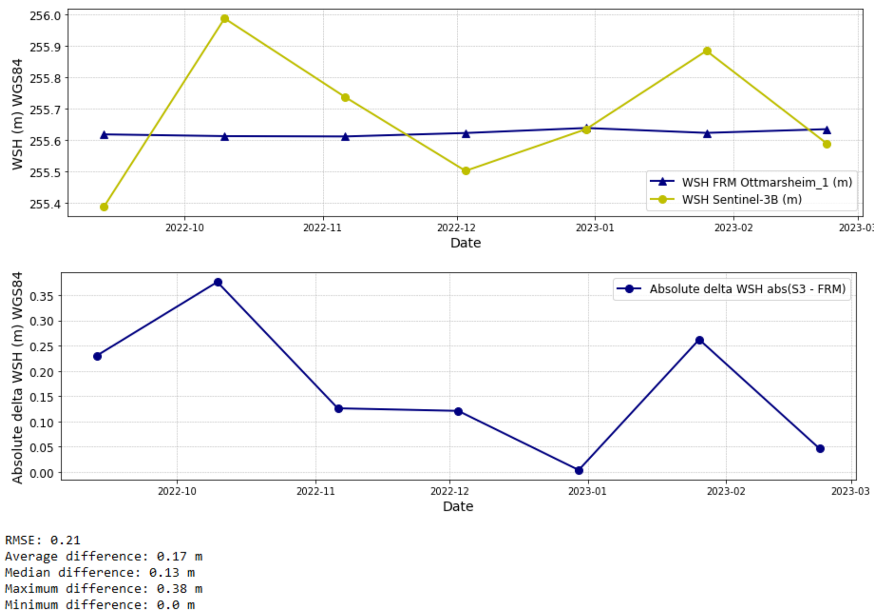


Figure 65: Time Series Analysis of Sentinel-3/FRM Comparison on Ottmarsheim site selecting the Sentinel-3 measurement that minimizes the difference with the FRM value

Results of the comparison on each site using the last approach will be detailed in the sections below.

<u>"Gerstheim" super site:</u>

Since Gerstheim is a level 0 super-site, the FRM simply corresponds to the micro-station measurement at the time t. This vortex station is located on the old arm of the Rhine, about 10 meters below the Rhine of the Grand Canal d'Alsace. The closest Sentinel-3B ground track used for the comparison corresponds to the relative orbit number 236, parallel to all the super sites analysed in this section.

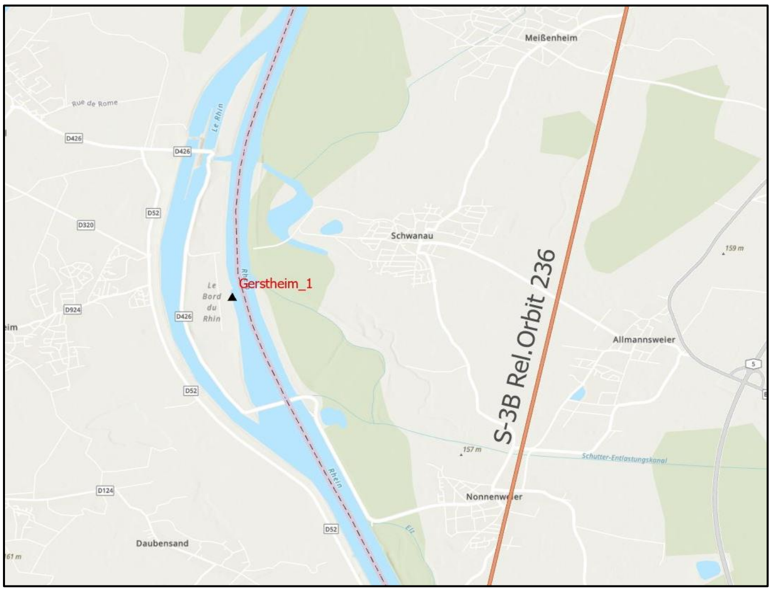
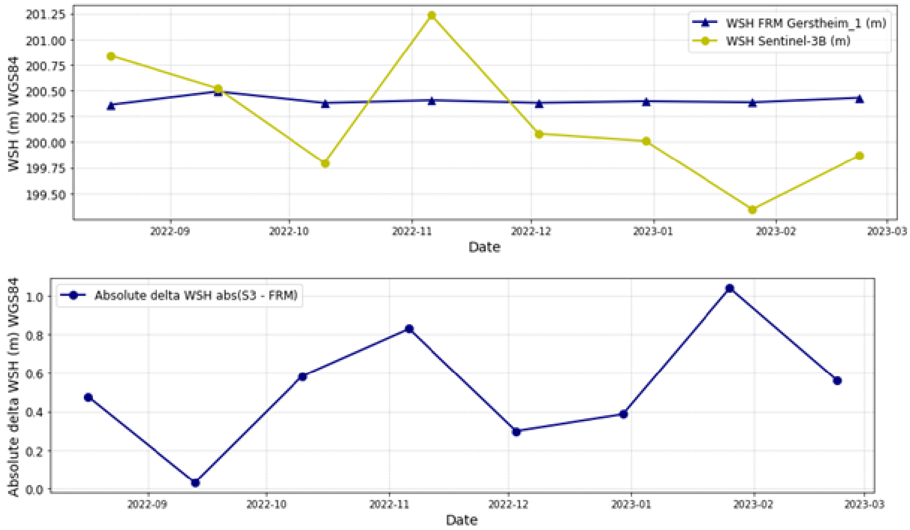


Figure 66: Map illustrating the location of the Gerstheim Station, the Rhine's centreline, and the theoretical path of Sentinel-3B




```
RMSE: 0.6
Average difference: 0.53 m
Median difference: 0.52 m
Maximum difference: 1.04 m
Minimum difference: 0.03 m
```

Figure 67: Time Series Analysis of Sentinel-3/FRM Comparison on Gerstheim site. The WSH delta is in absolute value. The RMSE is high, but the absolute average difference remains correct.

For Gerstheim, a time series was obtained with at least one Sentinel-3 measurements per cycle in the Old Rhine. Consequently, no significant difference is observed, such as leaps of several meters. We obtain a **RMSE** of **0.6 m** over all cycles. However, on two dates, November 2022 and February 2023, there was almost a 1m difference, suggesting the possibility that Sentinel-3 observed one of the nearby lakes, rivers, or another level of the river branch, upstream or downstream.

<u>"Ottmarsheim" super site:</u>

Ottmarsheim is a level 0 super-site, so the FRM simply corresponds to the micro-station measurement at time t. However, it is also a level 2 site with a strong dynamic. But in the absence of drone data for this site, it was treated as level 0. This station is located on the Old Rhine, a few meters east of the Chalampé micro-station.

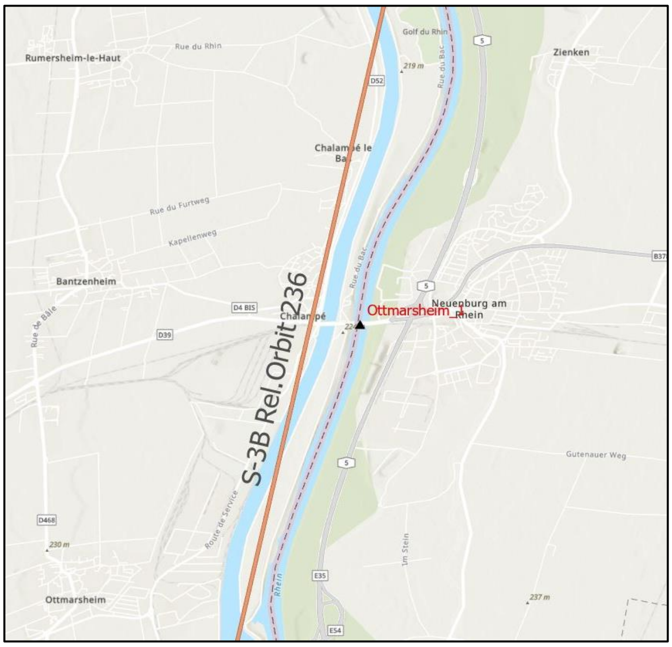


Figure 68: Map illustrating the location of the Ottmarsheim station, the Rhine's centreline, and the theoretical path of Sentinel-3B

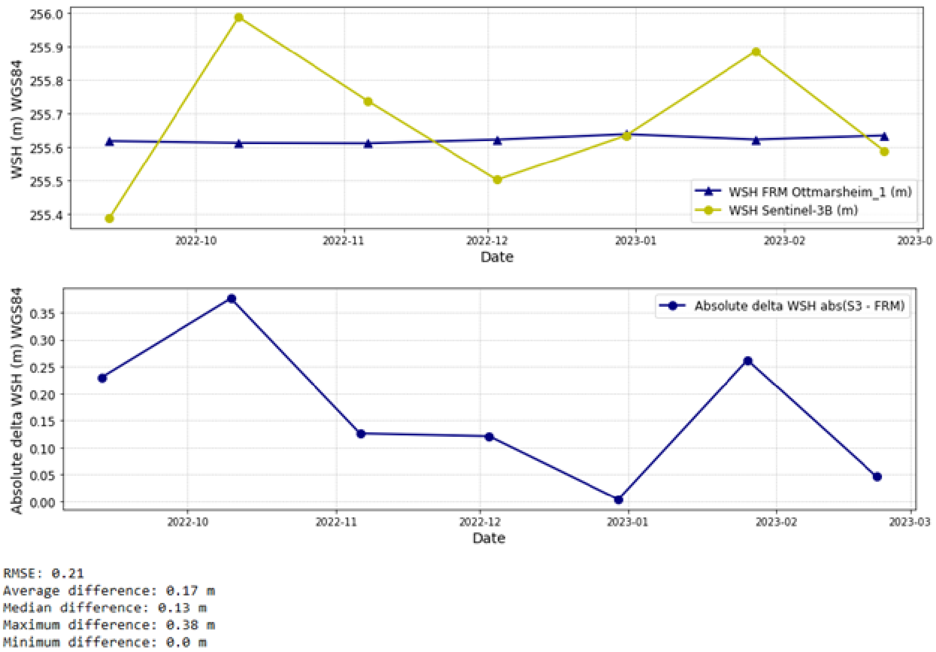


Figure 69: Time Series Analysis of Sentinel-3/FRM Comparison on Ottmarsheim site. We observe a very good RMSE as each cycle featured a well-localized measurement.

With an **RMSE** of **21cm** over 7 cycles and an absolute **average difference** of **17cm**, the time series for the Ottmarsheim station displays very good results. Over two cycles, the WSH difference increases to 40cm and 30cm. These measurements are not taken from the Grand Canal of Alsace. They could be measurements upstream or downstream or from a nearby water body close to the Sentinel-3 track.

"Chalampé" super site:

“Chalampé” is a level 1 super-site. Due to the Sentinel-3 track along the Rhine, acquisition can be done upstream or downstream of the station, and slope must be taken into account. A drone flight carried out in September 2022 enables the inclusion of slope correction in the comparison. Chalampé faces the same topological issues as Ottmarsheim, and Sentinel-3 views in the wrong arm of the Rhine can be expected for some cycles.

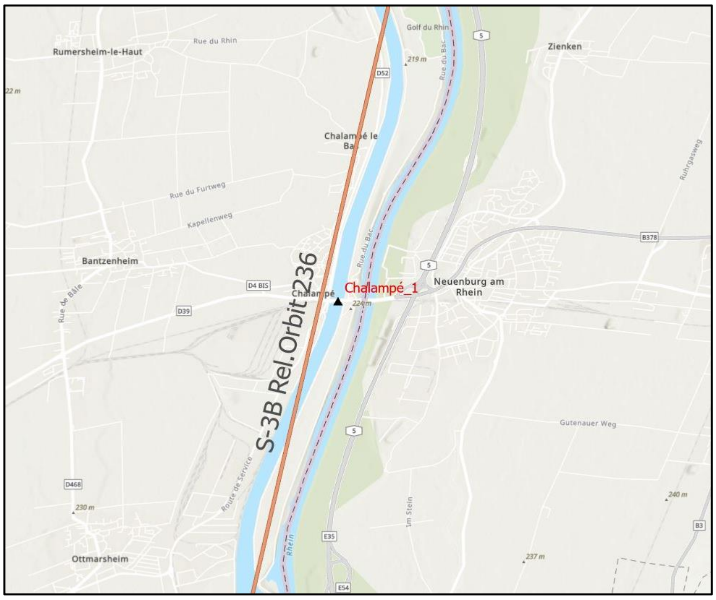
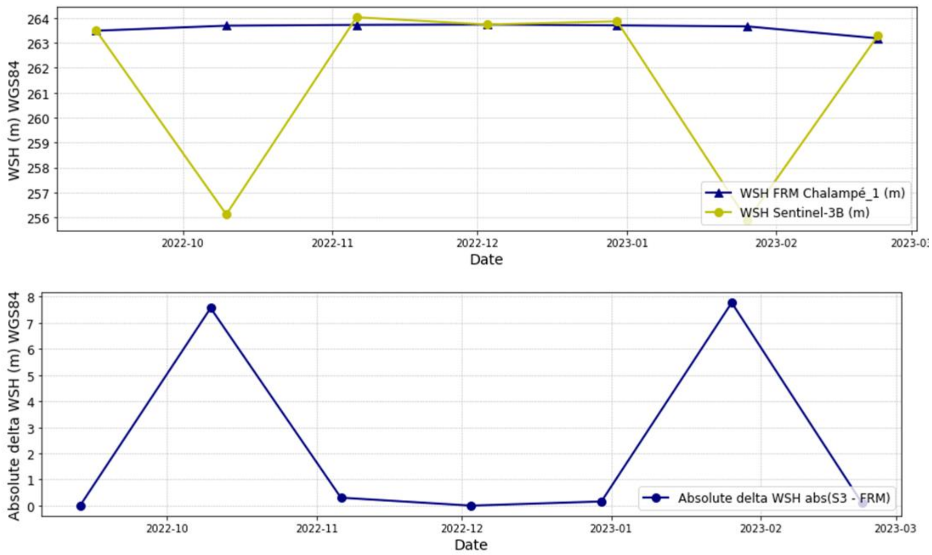


Figure 70: Map illustrating the location of the Chalampé station, the Rhine's centreline, and the theoretical path of Sentinel-3B




```
RMSE: 4.1
Average difference: 2.27 m
Median difference: 0.16 m
Maximum difference: 7.76 m
Minimum difference: 0.0 m
```

Figure 71: Comparison between the FRM measurement and the Sentinel-3 measurement on Chalampé site. Cycles 71 and 75 do not contain valid measurements and correspond to WSH (water sampling height) from the old Rhine section.

For “Chalampé” super site, the discrepancies come from the Sentinel-3 measurements taken on the wrong branch of the Rhine compared to our station, due to the complexity of the region. Indeed, some cycles have no valid measurements, which strongly impacts the time series and statistical indicators. However, in cases where the Sentinel-3 measurement targets the correct arm of the Rhine, a small WSH delta is observed.

"Gambsheim" super site:

"Gambsheim" is a Level 1 super-site. The processing includes a slope correction using data from the drone flight conducted over the area. The station comprises an upstream and downstream survey of the EDF dam, which provides the data.

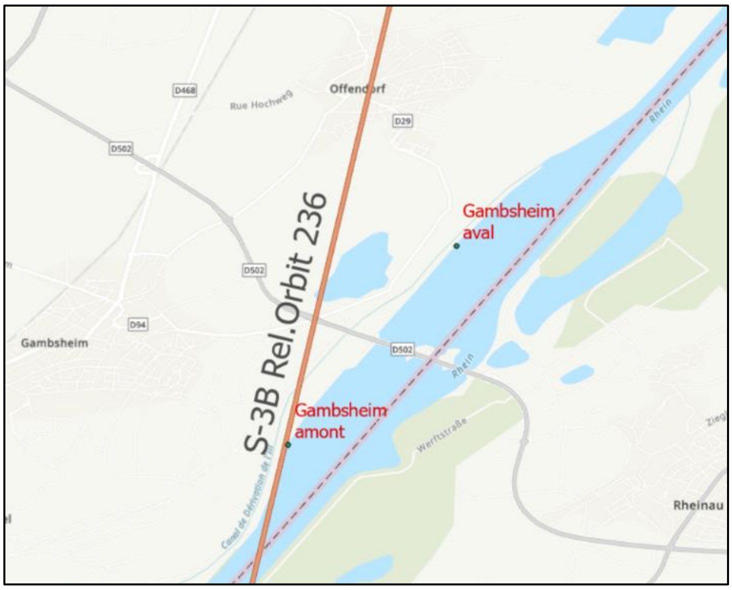


Figure 72: Map showing the location of the Gambsheim Upstream and Gambsheim downstream stations.

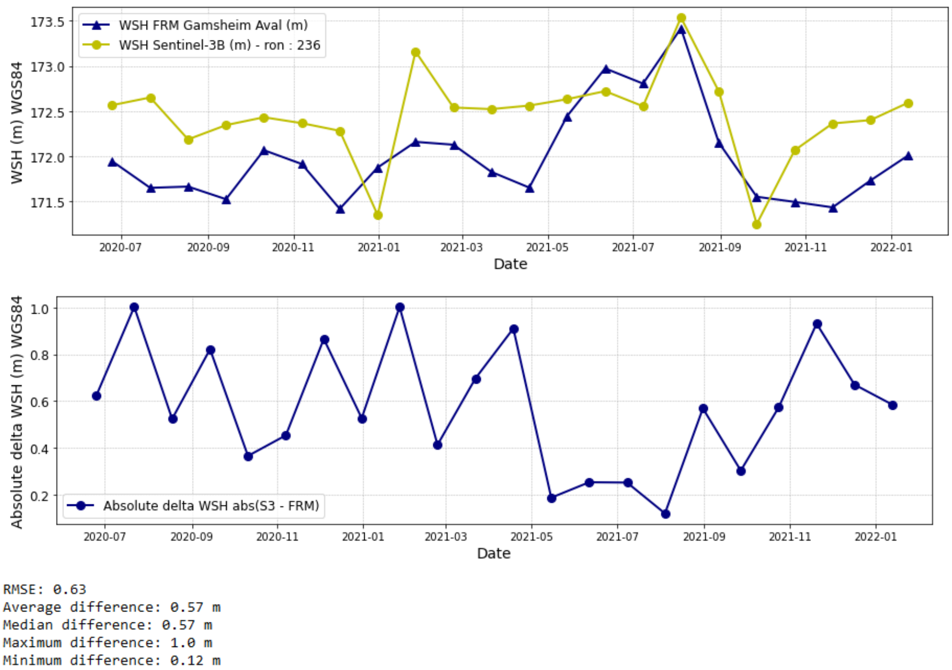
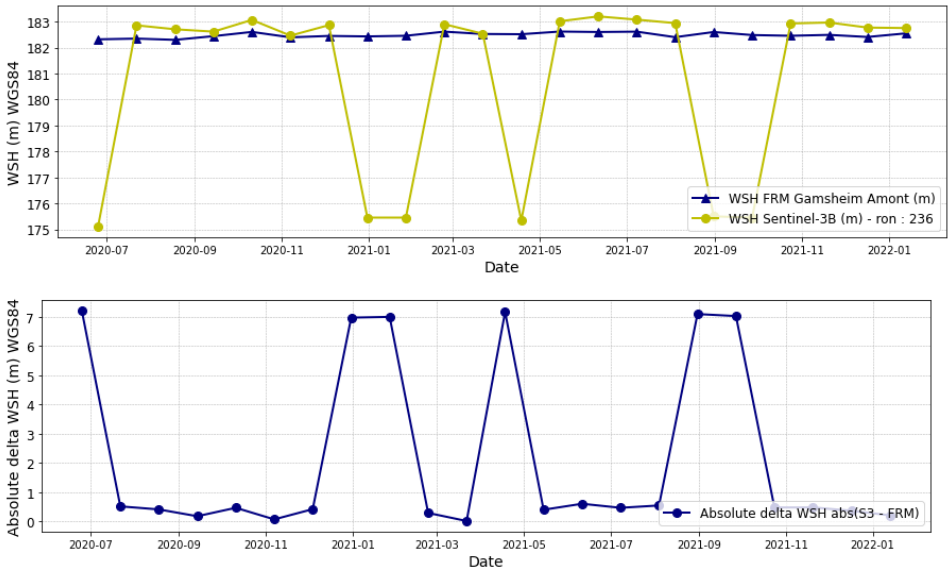


Figure 73: Comparison between the in-situ measurement (EDF station) and the Sentinel-3 measurement on Gambsheim Downstream site.

The time series for the downstream station appears to include at least one downstream Sentinel-3 measurement per cycle, which provides satisfactory results with an **RMSE** of **0.63 m**. Unfortunately, significant discrepancies have been observed (absolute deviation > 0.4 cm), which negatively impact the overall results. The presence of water bodies adjacent to the river could potentially play a role in this degradation.




```
RMSE: 3.72
Average difference: 2.2 m
Median difference: 0.47 m
Maximum difference: 7.21 m
Minimum difference: 0.01 m
```

Figure 74: Comparison between the in-situ measurement (EDF station) and the Sentinel-3 measurement on Gambsheim Upstream site.

For the upstream station, it can be observed that some Sentinel-3 measurements, target the downstream area rather than the upstream region. For the other cycles, the data exhibits a reasonable correspondence illustrated by a median of the absolute delta equal to 0.47 m.

<u>"Strasbourg" super site:</u>

"Strasbourg" is a level 1 super-site. For this station, we have drone footage acquired in September 2022. The area is very complex, with multiple water bodies and the two branches of the Rhine River separated by the Rohrschollen Island. The Sentinel-3 track being to the east, the Old Rhine and the water bodies are closer to the satellite track than the Strasbourg_1 station.

Figure 75: Map illustrating the location of the Strasbourg station, the Rhine's centreline, and the theoretical path of Sentinel-3B

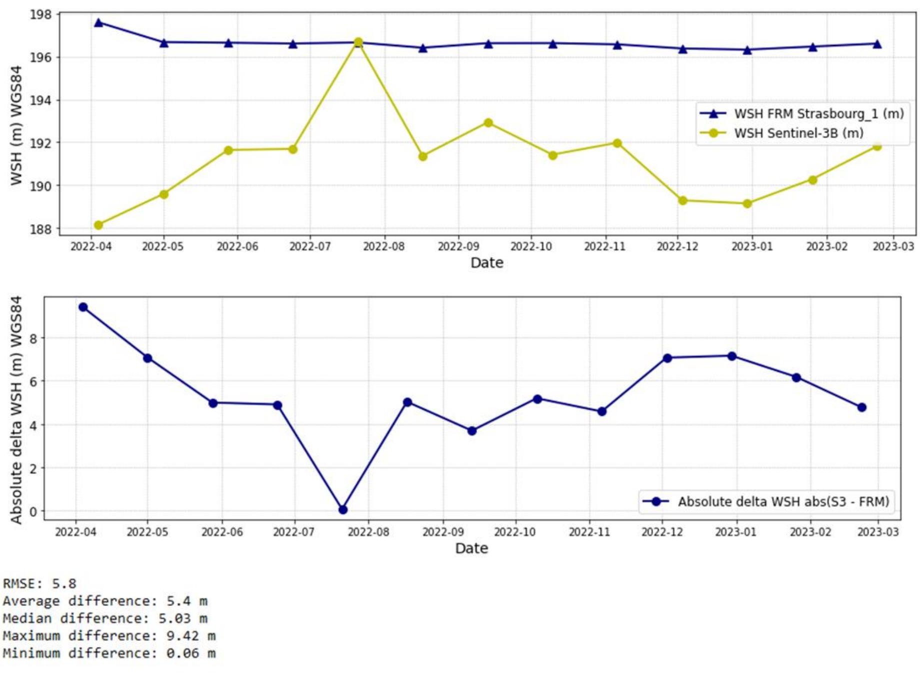


Figure 76: In this time series, only cycle 68 (end of July 2022) allows us to compare our data with the Sentinel-3 measurement. No other measurements in each of the cycles were able to acquire water level data for the correct branch of the Rhine.

Unfortunately, at the "Strasbourg" super site, only one cycle has been observed in which Sentinel-3 recorded at least one measurement on the appropriate branch, presenting a delta WSH of 6 centimetres. In the remaining instances, the measurements were collected from an incorrect branch of the Rhine in relation to our monitoring station, which can be attributed to the region's intricate geography. We chose to install the micro-station on the western arm of the Rhine to investigate the capability of Sentinel-3 to perform good off-nadir measurements. Unfortunately, Sentinel-3 almost never perform measurements on this arm of the Rhine. Following this result, the "Strasbourg" super site should not be maintained as it is. The micro-station should be moved to the eastern arm of the Rhine River to perform comparison on every cycles.

5.2.3 Conclusion on the Rhine River (French part) site

The Rhine River is a very interesting site because of the river configuration. Indeed, 2 branches of the Rhine River are separated from few hundred meters and with a level difference up to 10 m are seen by Sentinel-3 (present in the radar footprint). The processing defined in the TD-6 [RD6] document allows to provide good FRM with little adjustments due to the site characteristics (which consists in separating the Sentinel-3 measurements on the 2 branches). This site also demonstrates the capability of Sentinel-3 to measure both branches. The computed performances are very good with an RMSE of 21 cm on Ottmarsheim and Chalampé and 60 cm on Gerstheim.

The Erstein site has been installed to investigate the capability of the satellite to measure 2 different water surface height on either side of a lock dam. As it has been positioned under a Sentinel-6 track for R&D activity, these stations will not be maintained for the needs of Sentinel-3.

The Strasbourg site has been installed to investigate the capability of Sentinel-3 to provide relevant off-nadir measurements. It appears that Sentinel-3 only measures the closest branch of the Rhine from its theoretical ground track. In this context, this Micro-Station should be moved on the closest branch of the Rhine to be used.

In Gambsheim, it has been investigated the possibility to use existing sensor (EDF data) as super site with a river topography measured by a drone campaign. Even if the results are not dramatically bad (RMSE of 63 cm) we struggled during the project to get the data from EDF. It demonstrated that we cannot rely on data from external provider for an operational provision.

6 The Rhine and Neckar Rivers (German part)

6.1 Campaign performed on the site

On the German part of the “Rhine River” and its tributary the “Neckar” we performed a campaign to install 3 in-situ sensors on 3 different “super sites”: “Oestrich-Winkel”, “Mannheim” and in “Esslingen am Neckar”. Sentinel-3A ground tracks cross the Rhine River and the Neckar near the locations where we installed the Micro-Stations. These sites have been chosen because the “Rhine River” and the “Neckar” are canalized waterbodies. The Neckar is controlled by successive dams, but the Rhine River is less controlled than in the French part presented in the above paragraph. There are less dams than in France, but the discharge of the “Rhine River” is controlled by a large network of canals. The geometry on all the sites is also very interesting. In “Oestrich-Winkel” and in “Esslingen am Neckar”, the Sentinel-3A ground track crosses respectively the “Rhine River” and the “Neckar”. On “Mannheim” the Sentinel-3A ground track is colinear with the “Rhine River” and the “Neckar” because the satellite exactly overflies the mouth of the “Neckar” into the “Rhine River”. They are ideal cases to evaluate the best possible performances that can be achieved by Sentinel-3 with this geometry. All the stations are not installed on the same waterbody. Further explanations on the choice of these sites are on the TD-6 document [RD6]. The full campaign is described on the corresponding campaign logs [RD18].

The first step of the data analysis is the computation of the reference height of the Micro-Station from the GNSS measurements recorded by the Septentrio base. This procedure is described in the TD-12 document [RD18]. We performed a GNSS measurement on each site. In the next paragraph we will present the results of the positioning of all the Micro-Stations and a short analysis of the data acquired since the installation.

__Oestrich-Winkel:__

The PPP positioning of the base provides excellent results with a median height of **132.599 m (WGS84)** with a standard deviation of **1.3 cm**. During this GNSS measurement the base tracked **13.5 satellites** in average. The rope access technicians have measured a vertical distance between the Micro-Station and the centre of phase of the GNSS base of **2.44 m**. It results in a reference height for the Micro-Station of **130.159 m (WGS 84)** in ellipsoidal height. We have not access to the German geoid, so it is impossible to provide measurement in the local geoid.

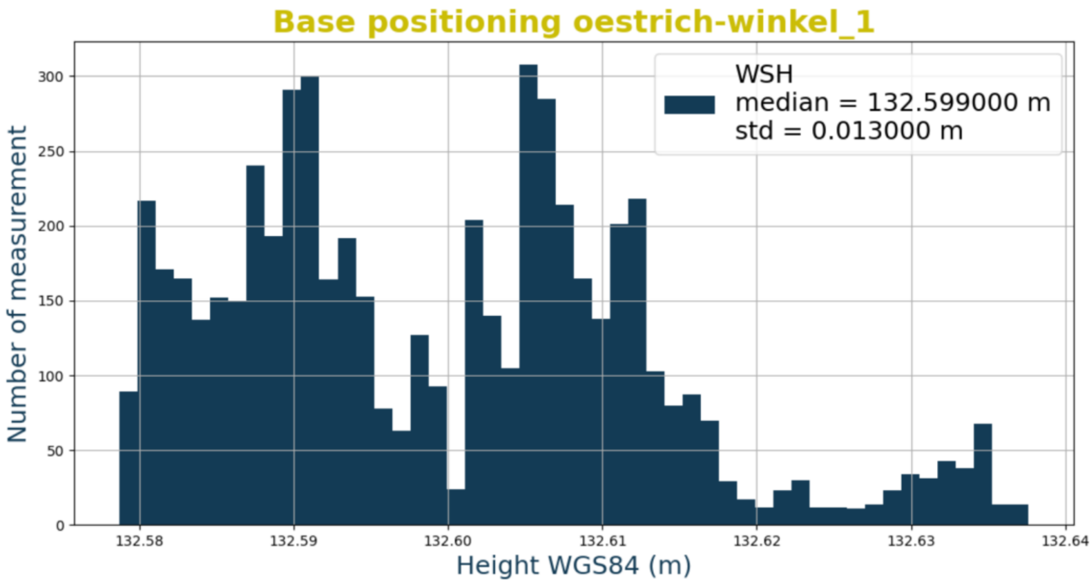


Figure 77: Histogram of the altitudes of the base computed by PPP for “oestrich-winkel_1”

The combination of this GNSS processing and the LiDAR measurements provides the precise altitude of the water measured by the Micro-Station. We obtain the time-series measured by the Micro-Station “oestrich-winkel_1” (Figure 78)

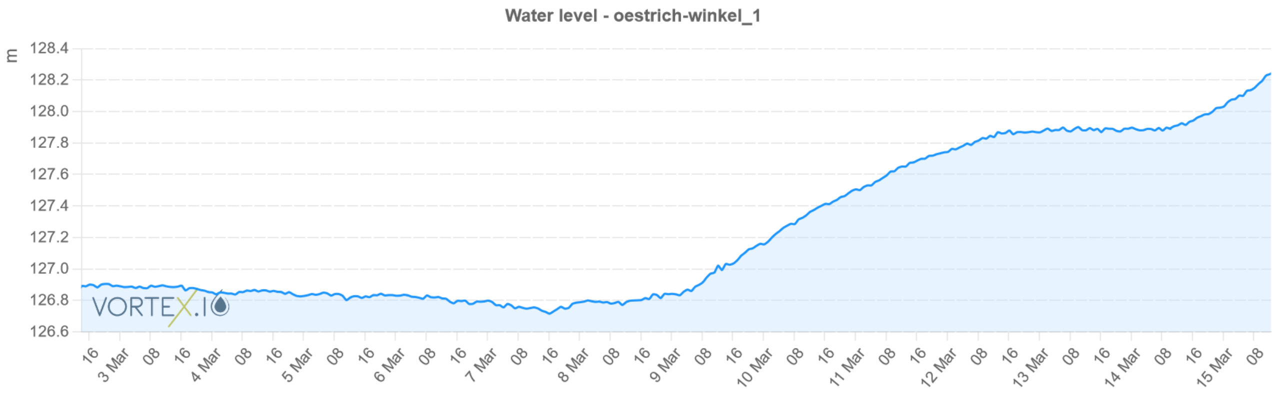


Figure 78: Time series of water surface height measured by the station labelled " oestrich-winkel_1" since the installation

The data measured by “oestrich-winkel_1” is very smooth. We can observe a constant rise of the water level since the 9th of March. The quality of the data is excellent.

Mannheim:

The PPP positioning of the base provides good results with a median height of **150.879 m (WGS84)** with a standard deviation of **1.8 cm**. During this GNSS measurement the base tracked **13 satellites** in average. The rope access technicians have measured a vertical distance between the Micro-Station and the centre of phase of the GNSS base of **2.196 m**. It results in a reference height for the Micro-Station of **148.683 m (WGS84)** in ellipsoidal height. We have not access to the German geoid, so it is impossible to provide measurement in the local geoid.

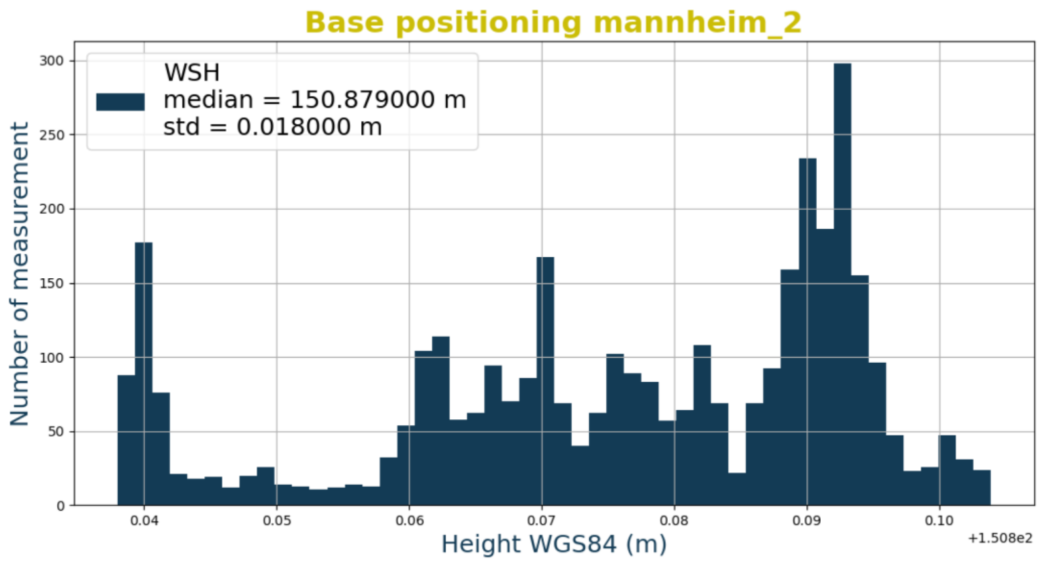


Figure 79: Histogram of the altitudes of the base computed by PPP for “mannheim_2”

The combination of this GNSS processing and the LiDAR measurements provides the precise altitude of the water measured by the Micro-Station. We obtain the time-series measured by the Micro-Station “mannheim_2” (Figure 80). The station is labelled “Mannheim_2” because we already have installed a micro-station in Mannheim in the framework of the SWOT project.

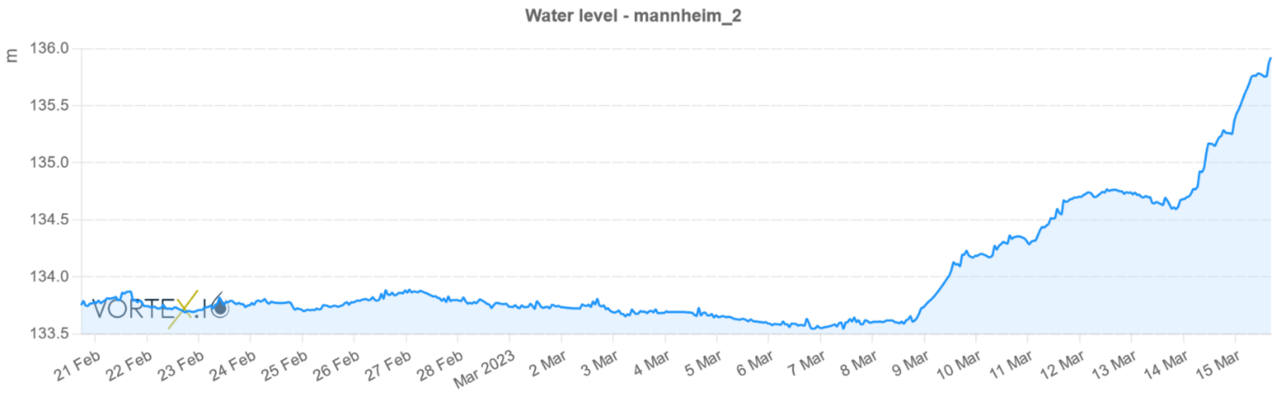


Figure 80: Time series of water surface height measured by the station labelled " mannheim_2" since the installation

The data measured by “Mannheim_2” is very stable. The Micro-Station is installed on the “Neckar River”, a controlled waterbody. The quality of the data is excellent too.

Esslingen-am-Neckar:

The PPP positioning of the base provides good results with a median height of **299.639 m (WGS84)** with a standard deviation of **1.1 cm**. During this GNSS measurement the base tracked **13 satellites** in average. The rope access technicians have measured a vertical distance between the Micro-Station and the centre of phase of the GNSS base of **1.490 m**. It results in a reference height for the Micro-Station of **298.149 m (WGS84)** in ellipsoidal height. We have not access to the German geoid, so it is impossible to provide measurement in the local geoid.

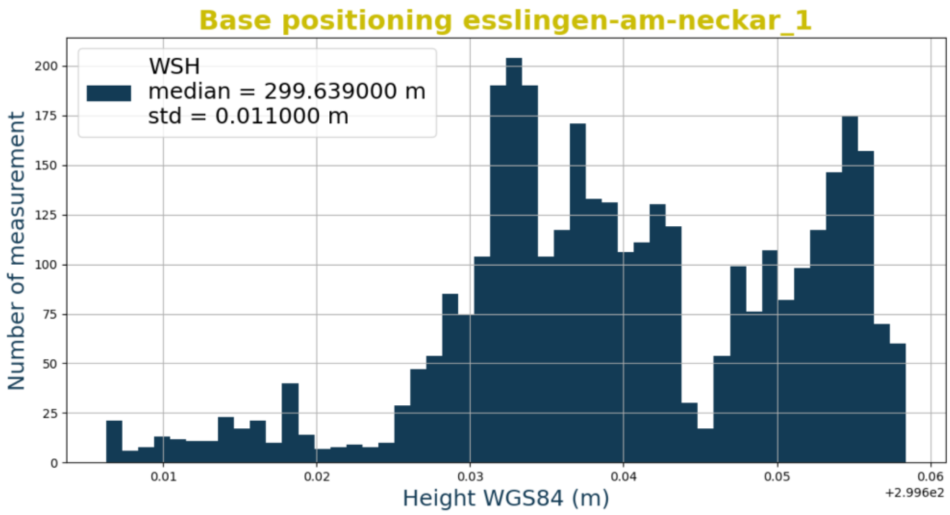


Figure 81: Histogram of the altitudes of the base computed by PPP for “esslingen-am-neckar_1”

The combination of this GNSS processing and the LiDAR measurements provides the precise altitude of the water measured by the Micro-Station. We obtain the time-series measured by the Micro-Station “Esslingen-am-neckar_1” (Figure 82)

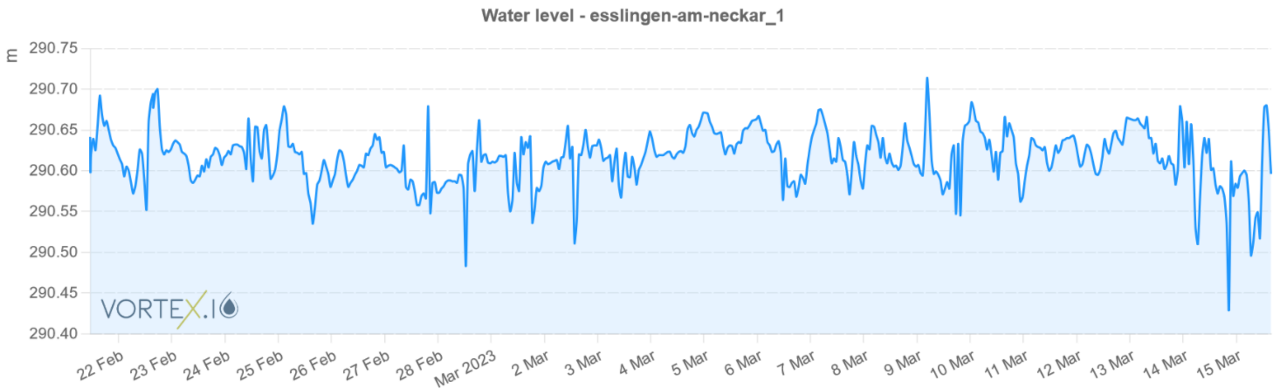


Figure 82: Time series of water surface height measured by the station labelled " Esslingen-am-neckar_1" since the installation

The data measured by "Esslingen-am-neckar_1" is very stable. The Micro-Station is installed on the "Neckar River", upstream of a hydrological control, that explains the stability of the time-series. The data is noisy, but the measurements are still very precise.

6.2 Computing FRM on the Rhine and Neckar Rivers

6.2.1 Computing the FRM

Following the Cal/Val site classification detailed in the TD-6 document (RoadMap) [RD6], all the sites correspond to complexity level 0 site except the site in "Esslingen am Neckar" that corresponds to a complexity level 1.

Complexity level 0 sites:

On complexity level 0, thanks to the installation of the instrumentation described in the previous paragraph: a vorteX.io Micro-Station on each site, and following the recommendations related to this site class, we can compute the FRM measurement and then compare to Sentinel-3 data.

As mentioned before these sites correspond to complexity level 0 site. The in-situ sensors are installed just under the satellite ground tracks. The computation of the FRM is very simple: there is no slope to be accounted for, no other in-situ data required, the measurement of the in-situ sensors can be performed at the exact same time as the satellite passes. The FRM simply corresponds to the measurements of the vorteX.io Micro-Stations that have been configured to perform a measurement at the exact time of the Sentinel-3A pass. The Equation of the FRM on these sites is:

$$\boldsymbol{WSH_{FRM}(t)} = \boldsymbol{WSH_{IS}(t)}$$

Complexity level 1 site:

On the "Esslingen am Neckar" super site the Micro-Station is not installed just under the Sentinel-3 ground track. The Neckar on this section is canalized and the slope between the Micro-Station and the virtual station is controlled. With other in-situ data it is possible to measure the slope. This slope is linear because the waterbody is canalized. This slope never changes with the water level. The distance between the Micro-Station and the virtual station is short and the waterbody is not very dynamic so there is no propagation time to be accounted for. With all these parameters, we can tell that this site is a complexity level 1.

On complexity level 1, thanks to the installation of the instrumentation described in the previous paragraph: a vorteX.io Micro-Station and a slope measured by 2 in-situ sensors, and following the recommendations related to this site class, we can compute the FRM measurement and then compare to Sentinel-3 data.

As mentioned before this site corresponds to complexity level 1 site. The in-situ sensor is not installed just under the satellite ground tracks. The computation of the FRM is very simple: the slope must be accounted for, but no other in-situ data required, the measurement of the in-situ sensors can be performed at the exact same time as the satellite passes. The FRM simply corresponds to the measurements of the vorteX.io Micro-Stations that have been configured to perform a measurement at the exact time of the Sentinel-3A pass for the ground track #586 in "Esslingen am Neckar". This measurement is corrected by the slope measured with 2 in-situ sensors. The Equation of the FRM on these sites is:

$$WSH_{FRM}(t) = WSH_{IS}(t) + Slope$$

Prerequisites:

On the two complexity level 0 "super sites" there are no prerequisites for the computation of the FRM. On the complexity level 1 "super site" the prerequisites are presented in the next paragraph:

1. The centreline

A river centreline is needed for the FRM processing on the "Esslingen am Neckar" super site. This centreline is computed from a kml file built from a Google Earth trajectory, there are no precise centreline database easily accessible in Germany. The centreline is the curvilinear abscissa along the river. The computed centreline on the "Neckar River" for this super site is shown in Figure 83.

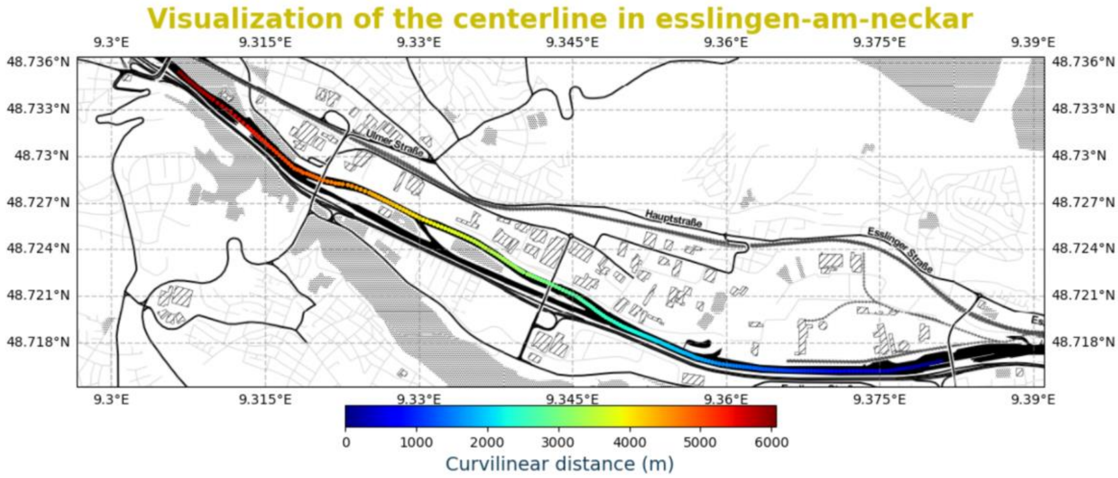


Figure 83: Visualisation of the centreline in "esslingen am neckar"

2. River topography measurements

As mentioned in the classification of the super sites [RD6], on complexity level 1 super sites the topography of the river is linear. In this "super site" the linearity of the slope is explained by the canalisation of the waterbody. A dam is present on the "Neckar River" 3 kilometres downstream. If the water profile is linear, we do not need a topography measurement with a moving sensor but a linear estimation of the slope with 2 in-situ sensors.

6.2.2 Comparison with Sentinel-3

This exercise has been performed by GIS team. The FRM is computed as described in the TD-6 document [RD6]. In the next paragraph we present the FRM processing performed for a complexity level 1 super site: "Esslingen-am-Neckar". The FRM processing for the complexity level 0 super sites is more straightforward. There is no slope to be accounted for. The step 3 must be ignored and the final FRM is simply the measurement of the micro-station at the time ***t***.

FRM Processing:

1. Load Sentinel-3 data and get the actual time *t* and location of the satellite measurements.

Sentinel-3 data are downloaded from the ESA Copernicus Open Access Hub (https://scihub.copernicus.eu/). The Figure 84 illustrates data from cycle 92 on the S3A ground track #293.

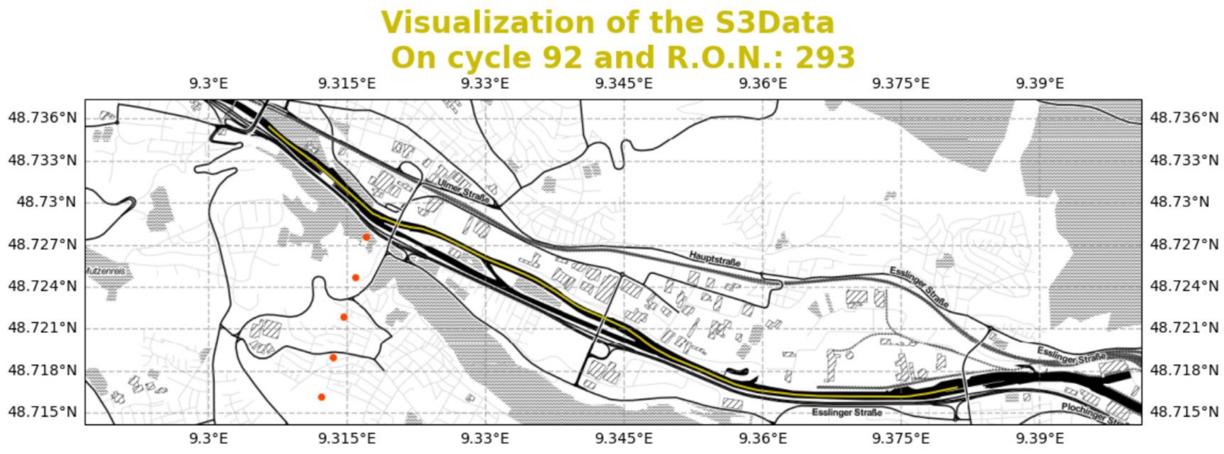


Figure 84: Map showing the positions of the S3A measurements on cycle 92 track #293 over the Neckar River

2. Compute the height at the reference station at ***t***

The ellipsoidal height measured by ”Esslingen-am-neckar_1” Micro-Station at ***t*** is selected (or interpolated if the time does not correspond exactly, i.e. less than 1 minute).

3. Compute the slope correction from the slope measurement

In principle, the most straightforward approach to determining slopes without a dense network of water surface measurements (e.g., on moving platforms) is to compare the heights of two relevant local gauges. In Esslingen am Neckar, orthometric height measurements of the river’s surface are non-existent for which reason the focus lies on the two nearby in-situ gauges operated by German national authorities.

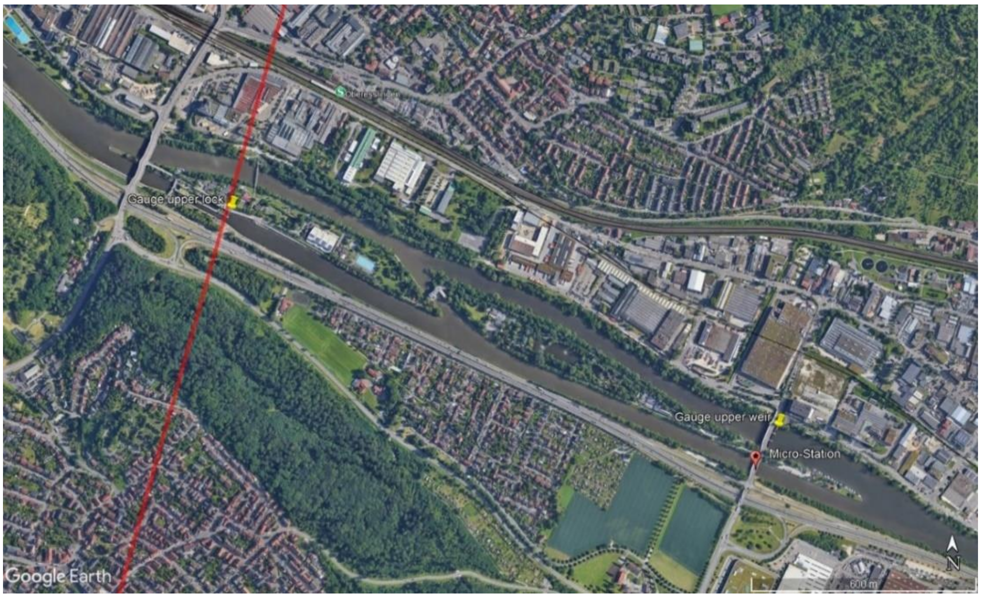


Figure 85: An overview of the local gauges, Micro-Station and S3A ground-track

The above figure depicts the locations of both in-situ gauges, the Micro-Station and the nominal ground-track of Sentinel-3A. If there is a significant slope in this reach of the Neckar River, it will be concluded from the height difference of the two available local gauges. According to the German national authorities both high water gauges at the lock and the weir are fixed at an ellipsoidal height of 288.349 m and consequently show that there is no significant slope to account for. Esslingen am Neckar remains a level 1 super site due to the considerable distance between the micro-station and Sentinel-3A's ground-track, yet in the end slopes are negligible.

4. Finally, the FRM value is computed combining the height at the reference station at ***t*** and the slope correction.

Due to a very long-lasting procedure of permission requests to German authorities the vorteX.io Micro-Station was just installed on 21. February 2023. Therefore, this super site does not yet contribute significantly to the validation of Sentinel-3A measurements over Esslingen am Neckar. However, as stated previously, the measurements of the Micro-Stations at the Dieter-Roser-Brücke can be assessed as very stable and precise. This location will turn out to be a reliable super site for future validation. Nonetheless, one Sentinel-3A observation was performed since the installation of the Micro-Station and hence can be compared to vorteX.io's measurements of the same epoch. Due to latency of non-time-critical data availability at the time of this writing, the comparison is performed with near-real-time data. In future FRM Campaign reports non-time-critical data will be available.

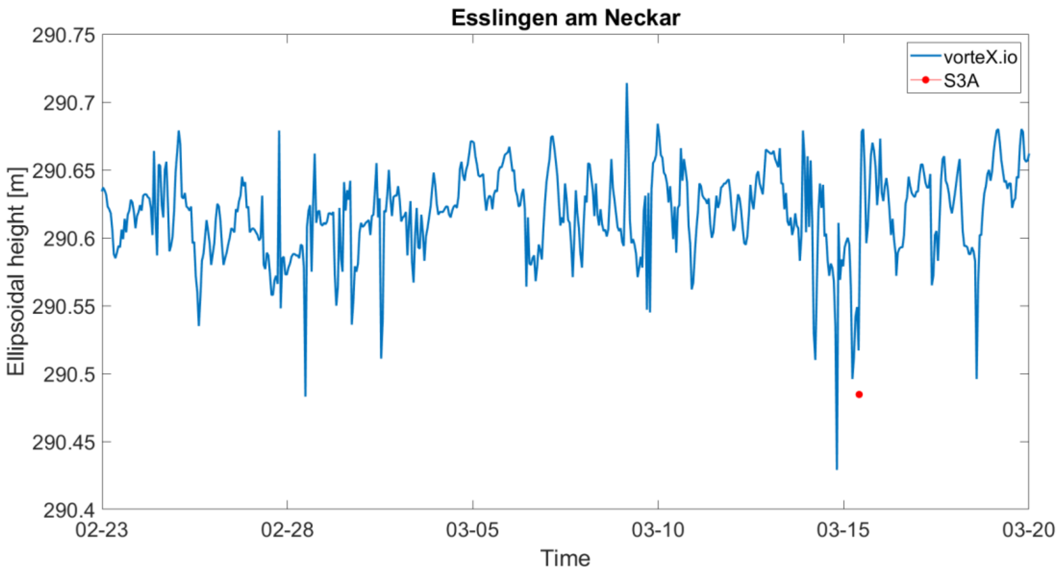


Figure 86: Water level time-series measured by vorteX.io and one altimetric measurement by S3A in Esslingen

The above figure demonstrates the water levels of the Neckar River in Esslingen observed by the Micro-Station (blue) and the single altimetric measurement (red dot). From visual inspection the altimetric measurement captured quite precisely the true water level when comparing it to the Micro-Station-derived water levels of approximately the same epoch. Numerically speaking, this difference amounts to only 3 cm. The investigation of this first comparable epoch proved to be quite promising and underlines the suitability of this super site in the future.

Just like in Esslingen am Neckar, the Cal/Val super site in Oestrich-Winkel only offers one altimetric measurement from Sentinel-3A due to the very recent installation (20 February 2023).

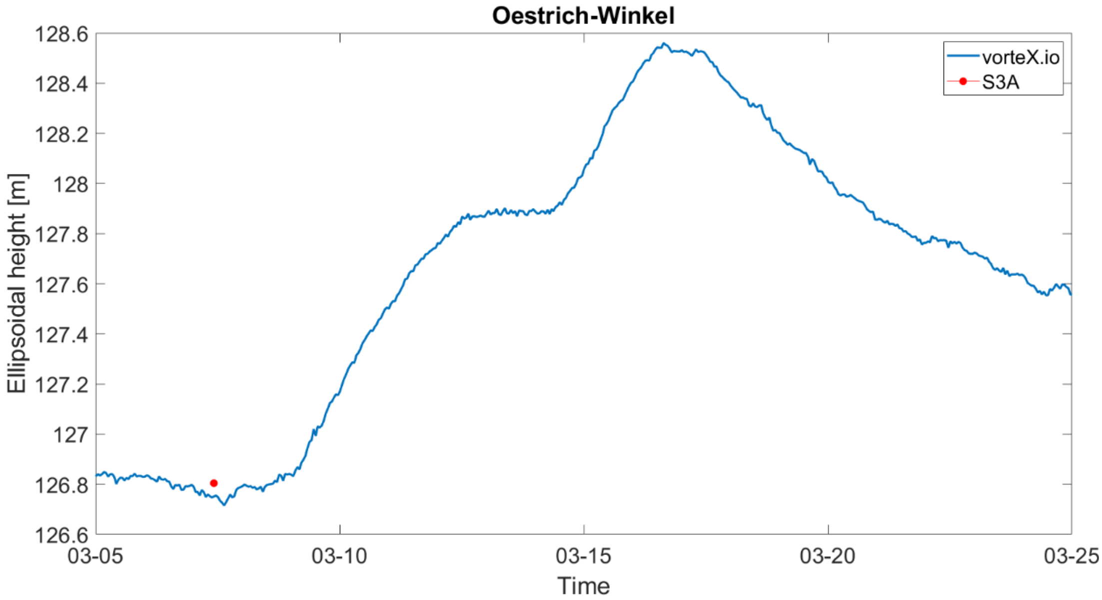


Figure: Water level time-series measured by vorteX.io and one altimetric measurement by S3A in Oestrich-Winkel

The above figure shows the water level time-series derived from the vorteX.io micro-station observations (blue) as well as the altimetric measurement (red dot). Similar to the Esslingen case, the Sentinel-3A measurement captured quite decently the true water level of the corresponding epoch. This visible difference amounts to only 5 cm which can thus be assessed as very precise. Future cycles will tell whether the agreement between observations from both sensors stays as promising as the single epoch presented in the figure.

Unlike the afore presented locations, the Mannheim Cal/Val super site does not yet provide comparable measurements between those of the vorteX.io micro-station and of Sentinel-3A. The satellite does pass by Mannheim on 05 March, but only comes close to the Rhine River in the Northern part of the virtual station. The altimetric measurements of this very epoch are, for one, several kilometres away from the installed micro-station and, for another, over the main part of the Rhine. The micro-station in Mannheim is installed over the final reach of the Neckar River, a tributary, before it flows into the Rhine. Therefore, the observations from the micro-station will only be used to validate those future altimetric measurements occurring over the last kilometres of the Neckar in Mannheim. The figure below visualizes the latest Sentinel-3A crossing at the Mannheim virtual station together with the location of the installed micro-station.

Figure: Latest Sentinel-3A crossing and location of micro-station in Mannheim

6.2.3 Conclusion on the German Rhine/Neckar sites

In the sections above, the measures for establishing a reliable FRM at the Cal/Val super sites Oestrich-Winkel, Mannheim and Esslingen as well as a first comparable epoch were presented. Esslingen am Neckar by definition is considered a Level 1 Cal/Val super site. However, the orthometric heights of two fixed in-situ gauges demonstrated that there is no slope to account for despite the distance between the installed micro-station and nominal ground-track of Sentinel-3A. Therefore, both the Esslingen and Oestrich-Winkel Cal/Val super sites can be taken for direct comparison between altimetric and micro-station-derived measurements. Due to the very recent installation of both micro-stations, it is only possible to compare their measurements to one epoch of S3A-data. As explained in the previous section, near-real-time data was used for the comparison due to latency of non-time-critical data availability at the time of this writing. Both show very favourable results in which the differences to the true water levels of corresponding epochs amount to 3 cm and 5 cm, respectively. For the single comparable epoch, the agreement between water levels derived from both sensors are very high. Future cycles will reveal how close the water level time-series stay to one another. At the Mannheim Cal/Val super site, it is not yet possible to validate Sentinel-3A measurements with the observations from the micro-station. The stability and quality of water levels derived from the micro-station, however, can already be assessed as very high. All in all, the first weeks of measurements by the three micro-stations show very promising time-series and will therefore be reliable FRMs for St3TART and potential follow-on projects.

These sites should be maintained to meet the long-term requirements of the MPC. It should be noted that a second site in Mannheim and a site in Sankt Sebastian was planned at the beginning of the project and can be installed now (permissions granted).

7 The Po River

7.1 Campaign performed on the site

7.1.1 In-Situ sensors

On the Po River we performed a campaign to install 4 in-situ sensors on 4 different "super sites": "Casale Monferrato", "Isola Pescaroli", "Boretto" and "Pontelagoscuro". Sentinel-3A and Sentinel-3B ground tracks crosses the Po River near the locations where we installed the Micro-Stations. These sites have been chosen because the Po River is a waterbody with a strong dynamic, the geometry of the sites is ideal (the Po River is mainly perpendicular to the Sentinel-3 ground tracks) and are therefore ideal cases to evaluate the best possible performances that can be achieved by Sentinel-3. 3 stations are installed under bridge crossing the Po River and the last station is installed on a boat dock structure. Further explanations on the choice of these sites are on the TD-6 document [RD6]. The full campaign is described on the corresponding campaign log [RD12]. The campaign was performed on the 11/04/2022 and 12/04/2022, the time-series are available since these dates.

The first step of the data analysis is the computation of the reference height of the Micro-Station from the GNSS measurements recorded by the Septentrio base. This procedure is described in the TD-12 document [RD12]. We performed a GNSS measurement on each site. In the next paragraph we present the results of the positioning of all the Micro-Stations and a short analysis of the data acquired since the installation.

<u>**"Casale Monferrato super site":**</u>

The PPP positioning of the base provides excellent results with a median height of **161.665 m (WGS84)** and a standard deviation of **1 cm**. During this GNSS measurement the base tracked **17 satellites** in average. The quality of the GNSS measurement is excellent. The rope access technicians have measured a vertical distance between the Micro-Station and the centre of phase of the GNSS base of **2.879 m**. It results in a reference height for the Micro-Station of **158.786 m** in ellipsoidal height. We have not access to the Italian geoid, so it is impossible to provide measurement in the local geoid at this time.

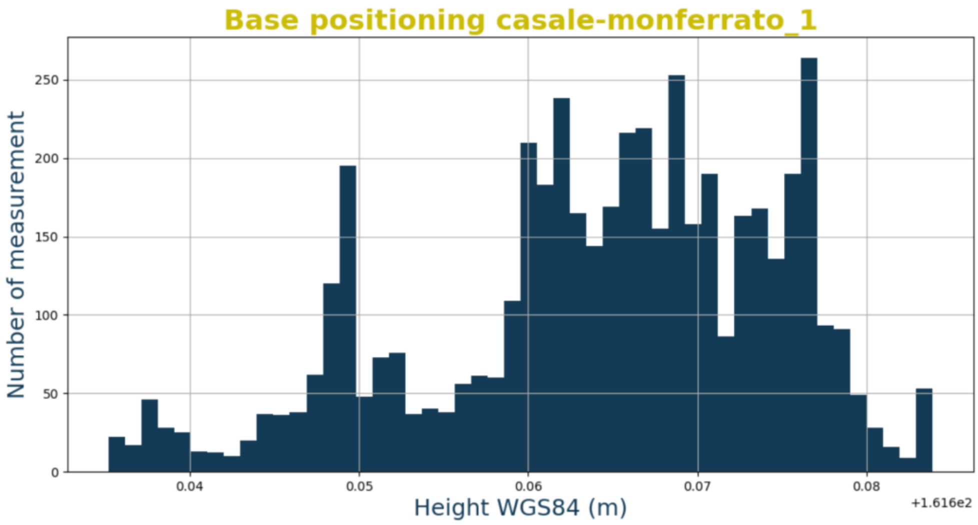


Figure 87: Histogram of the altitudes of the base computed by PPP for "Casale Monferrato"

The combination of this GNSS processing and the LiDAR measurements provides the precise altitude of the water measured by the Micro-Station. We obtain the time-series measured by the Micro-Station “casale_monferrato_1” (Figure 88).

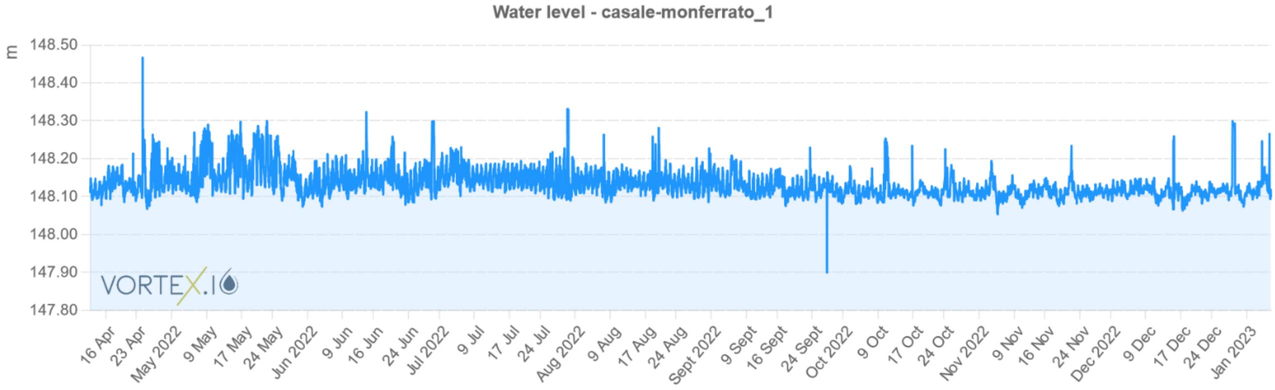


Figure 88: Time series of water surface height measured by the station labelled "casale_monferrato_1" since the installation

The water surface height on “casale_monferrato_1” is very stable. We expected a more dynamic waterbody, but a dam has been built few hundred meters downstream of the station. We were not aware of the building of this dam. Even if the waterbody is steadier than expected the quality of data is excellent.

<u>“Isola Pescaroli super site”:</u>

The PPP positioning of the base provides excellent results with a median height of **80.881 m (WGS84)** with a standard deviation of **2.1 cm**. During this GNSS measurement the base tracked **17 satellites** in average. The quality of the GNSS measurement is excellent. Rope access technicians have measured a vertical distance between the Micro-Station and the centre of phase of the GNSS base of **4.581 m**. It results in a reference height for the Micro-Station of **76.3 m** in ellipsoidal height. We have not access to the Italian geoid, so it is impossible to provide measurement in the local geoid.

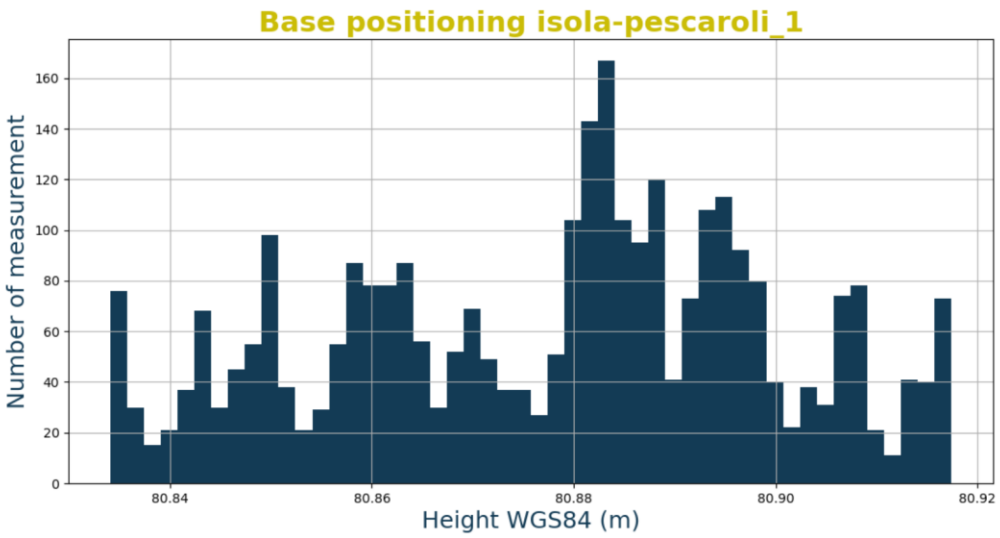


Figure 89: Histogram of the altitudes of the base computed by PPP for “Isola Pescaroli”

The combination of this GNSS processing and the LiDAR measurements provides the precise altitude of the water measured by the Micro-Station. We obtain the time-series measured by the Micro-Station "isola_pescaroli_1" (Figure 90).

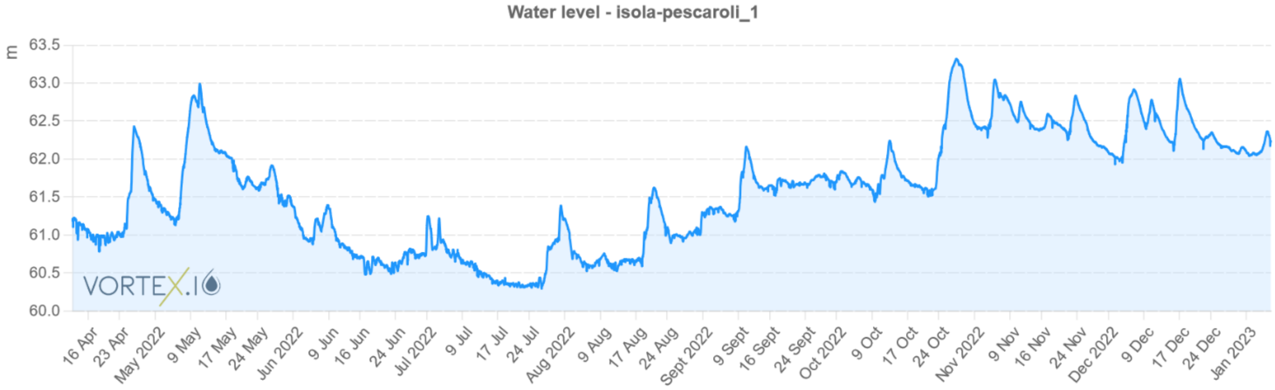


Figure 90: Time series of water surface height measured by the station labelled "isola_pescaroli_1" since the installation

We can see the evolution of the Po River through the year. Measurements are very precise. We can see that the water level decreases from April to the end of July and slowly increases during the end of summer and fall. We can see several flood events. During the period, the biggest flood event occurred in May and the frequency of these events increase during fall. As expected, the Po River is a very dynamic waterbody with a very different water height depending on the season. We expect that the topography of the river will depend on the water height.

"Boretto super site":

The PPP positioning of the base provides good results with a median height of **67.136 m (WGS84)** and a standard deviation of **2 cm**. During this GNSS measurement the base tracked **14 satellites** in average, lower than the previous GNSS measurements but still very good. The quality of the GNSS measurement is very good. Rope access technicians have measured a vertical distance between the Micro-Station and the centre of phase of the GNSS base of **1.624 m**. It results in a reference height for the Micro-Station of **65.512m** in ellipsoidal height We have not access to the Italian geoid, so it is impossible to provide measurements in the local geoid.

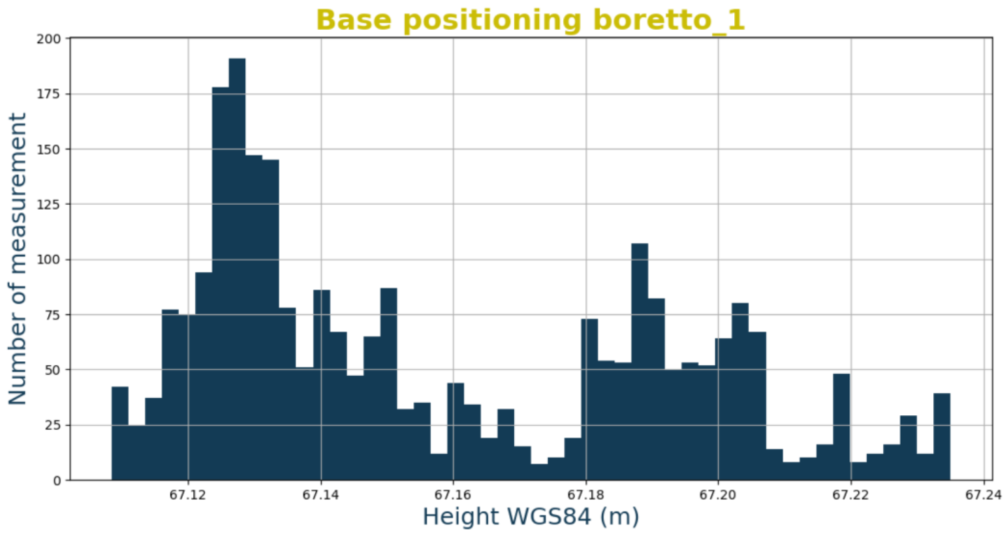


Figure 91: Histogram of the altitudes of the base computed by PPP for "Boretto"

The combination of this GNSS processing and the LiDAR measurements provides the precise altitude of the water measured by the Micro-Station. We obtain the time-series measured by the Micro-Station “boretto_1” (Figure 92).

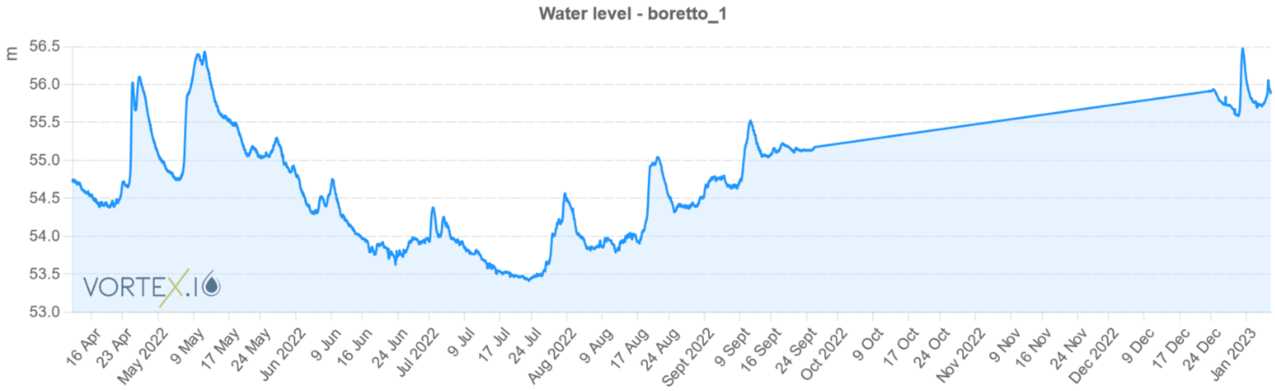


Figure 92: Time series of water surface height measured by the station labelled "boretto_1" since the installation

There is a gap of data between the beginning of October and the end of December. The Micro-Station had a problem and has been changed. Investigations are ongoing in vorteX.io to explain this failure and to fix the problem. In the meanwhile, we had to change the station to keep recording data. The data gap is bigger than expected because the change of the station was delayed. We sent the station on time, but we relied on the AIPO local team to change the Micro-Station and they changed it very lately. Besides this issue we can observe on the data the same water events in “Boretto” than in “Isola Pescaroli”. This is an excellent result; the 2 stations observe the same dynamic.

<u>“Pontelagoscuro super site”:</u>

The PPP positioning of the base provides good results with a median height of **59.564m (WGS84)** and a standard deviation of **3.5 cm**. During this GNSS measurement the base tracked **15 satellites** in average. The quality of the GNSS measurement is good, the standard deviation is higher than the previous installations, but we have a good confidence in the GNSS measurement. The rope access technicians have measured a vertical distance between the Micro-Station and the centre of phase of the GNSS base of **2.614 m**. It results in a reference height for the Micro-Station of **56.95m** in ellipsoidal height. We have not access to the Italian geoid, so it is impossible to provide measurements in the local geoid.

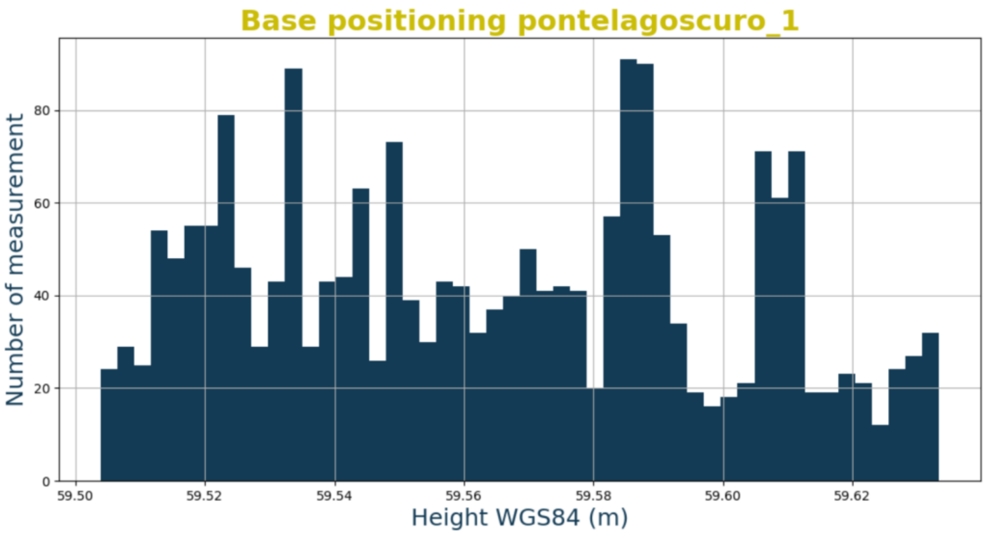


Figure 93: Histogram of the altitudes of the base computed by PPP for “Pontelagoscuro”

The combination of this GNSS processing and the LiDAR measurements provides the precise altitude of the water measured by the Micro-Station. We obtain the time-series measured by the Micro-Station “pontelagoscuro_1” (Figure 94).

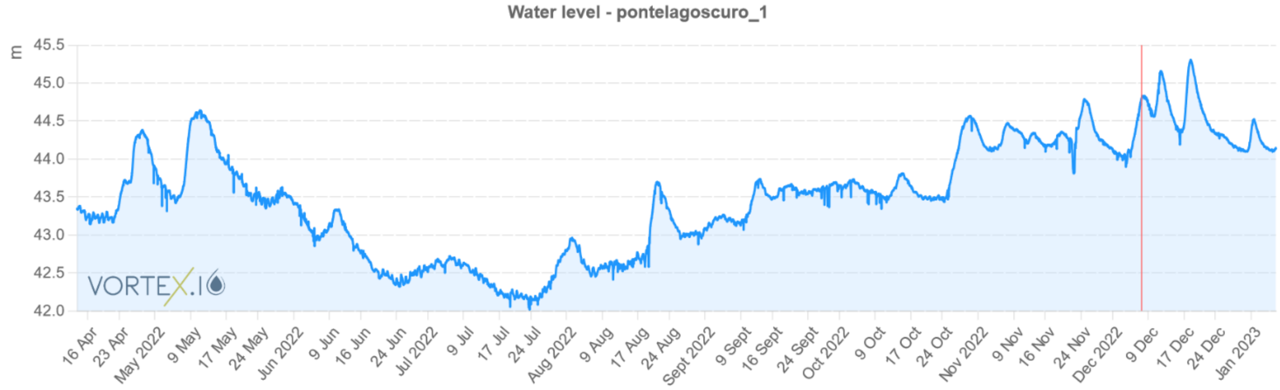


Figure 94: Time series of water surface height measured by the station labelled "pontelagoscuro_1" since the installation

We can see the evolution of the Po River through the year. The measurements are very precise, but noisier than the other sensors. We can see that the water level decrease from April to the end of July and slowly increase during the end of summer and fall. We can observe on the data the same water events in “Pontelagoscuro” than in “Isola Pescaroli” or “Boretto”. This is an excellent result; the 3 stations observe the same dynamic. We can see several flood events. Those flood events have a lower amplitude and a slower ascending speed in “Pontelagoscuro” than in “Isola Pescaroli” or “Boretto”. During the period, the biggest flood event occurred in May and the frequency of these events increase during fall. As expected, the Po River is a very dynamic waterbody with a very different water height depending on the season. “Pontelagoscuro super site” is closer to the mouth of the Po River and we can observe a different water dynamic.

The next figure (Figure 95) enlightens the correlation between the measurements of the 3 last Micro-Stations installed on the Po River.

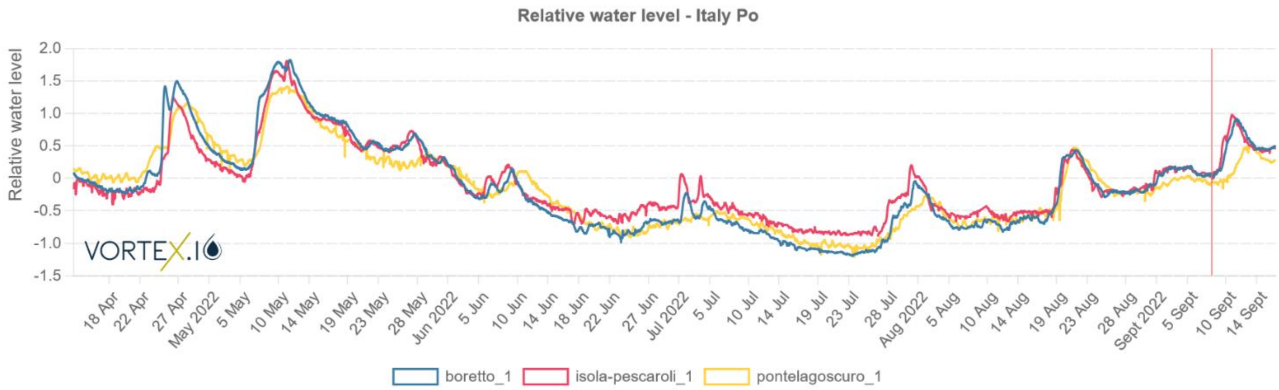


Figure 95: Comparison between the 3 vorteX.io Micro-Station located on the downstream part of the Po River

On this figure we can see the difference between the dynamic of the stations “Boretto” and “Isola Pescaroli” compared with the dynamic of the Micro-Station installed in “Pontelagoscuro”, downstream of the 2 others. As mentioned in the previous paragraphs, we can see that the 3 stations observe the same evolution of the water level. The downstream stations observe the floods after the 2 others, the shape of the flood events is less sharp, and the ascending speed is slower.

7.1.2 Moving Sensors

The Po River is a very dynamic river. The satellite ground tracks do not exactly overfly the Micro-Stations installed in the frame of the project. The topography of the river must be accounted to perform good FRM measurements. A campaign has been performed in order to measure the topography of the river in each super-site on the Po River. The discharge of the Po River was abnormally low when we performed the campaign. We only performed one campaign in the frame of the project, so we only have a low-water profile for the Po River. As the Garonne River, we assume that the topography will be different depending on the river stage, and on these sites, we assume that more drone flights will be useful to increase the accuracy of the FRM. The campaign was performed between the 07 and 10 November 2022, the campaign is fully described in the corresponding campaign log [RD21].

In the next paragraph we present the results of the campaign performed by the vorteX.io team in partnership with a drone pilot company I-TECHDRONE. The campaign was divided in 4 sites. The distance between the super sites is around 100 km. In order to obtain a precise positioning for the altimeter we had to perform a GNSS base measurement on each site. We'll present the results on the 4 super-sites in parallel. As for the Micro-Stations, the first data analysis we'll present is the positioning of the geodesic base and the positioning of the altimeter. Then we present the results of the data analysis of the LiDAR measurements. The procedure applied during these campaigns are described in the corresponding campaign logs [RD21].

The position of the base is obtained by performing a PPP (Precise Point Positioning) processing. On each site the obtained position of the base is very precise, with a standard deviation lower than **2.5 mm** on each site, as shown in Figure 96. The number of satellites tracked by the GNSS base during the acquisition time is around **18** in average. The satellites of the GALILEO, GPS and GLONASS constellations are used to perform the positioning. The quality of the positioning is very good. The base position is **69.936 m (WGS84)**. As for the Micro-Station we haven't access to the Italian geoid, so it is impossible to provide altitude in the local geoid.

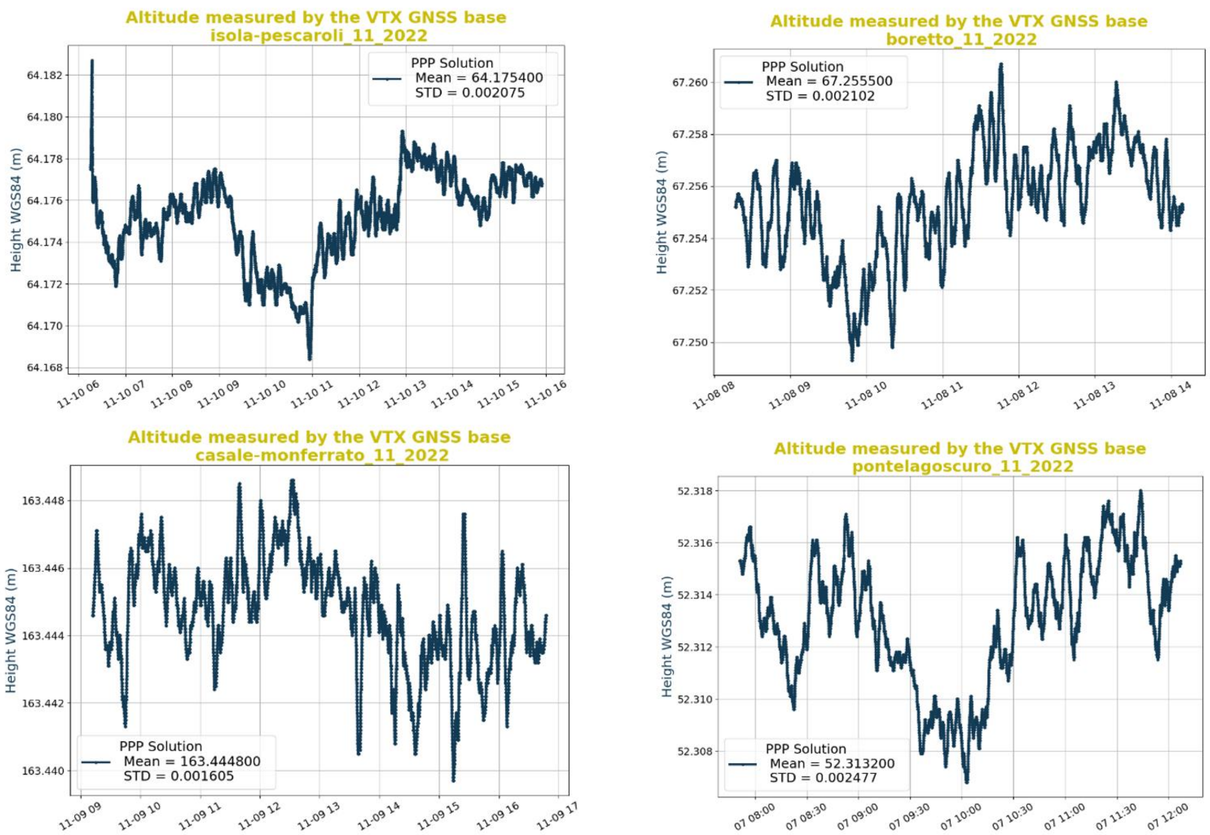


Figure 96: PPP positioning of the base on each super site on the Po River

Once the precise position of the base is computed, we can perform the PPK positioning of the altimeter. On 3 super-sites all the ambiguities are fixed when the altimeter is flying and thus the positioning is of good quality. On the "Pontelagoscuro" super-site we faced a lot of perturbation on the second part of the deployment. With this number of perturbations, it was impossible for us to compute a precise position for the altimeter on this part of the flights. We assume that the perturbations come from the presence of an airport close to the zone where we performed the measurements. This part of the flight has not been processed due to these perturbations. This is not an issue because "Pontelagoscuro" corresponds to a double super site for either Sentinel-3A and Sentinel-3B. The perturbations only affect one part of the super site. It will still be possible to perform comparison on this site with Sentinel-3A data.

We can see in Figure 97 the evolution of the altimeter altitude during the first flight of the campaign on each site. This precise positioning allows to get a precise water surface height measurement. The main difference with the previous campaign is the drone altitude.

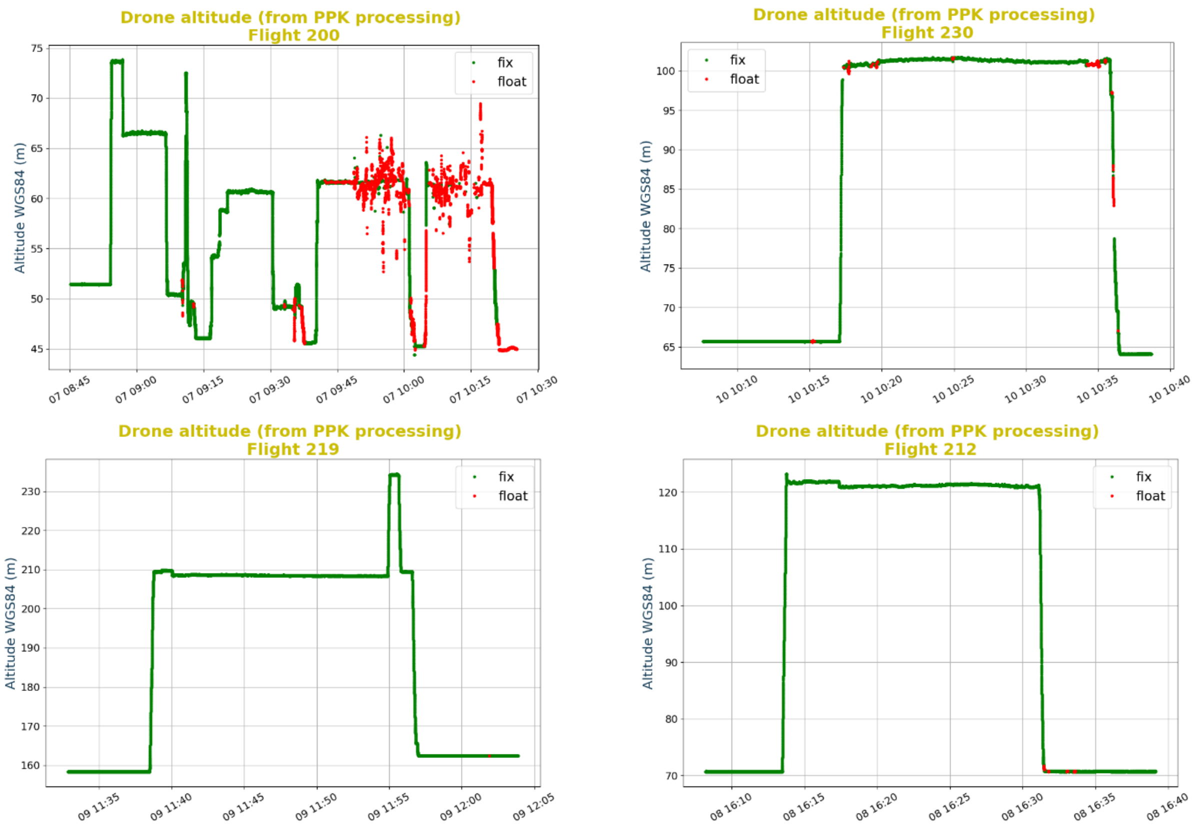


Figure 97: Altitude of the altimeter during the first flight on each site

Once the precise positioning computed, we can compute the water surface height from LiDAR measurements. We have applied a running mean (window of 15 seconds) on the WSH measured by the altimeter to decrease the measurement noise. The LiDAR measurements are performed at 7 Hz, and we finally resampled to 0.5 Hz for the data dissemination.

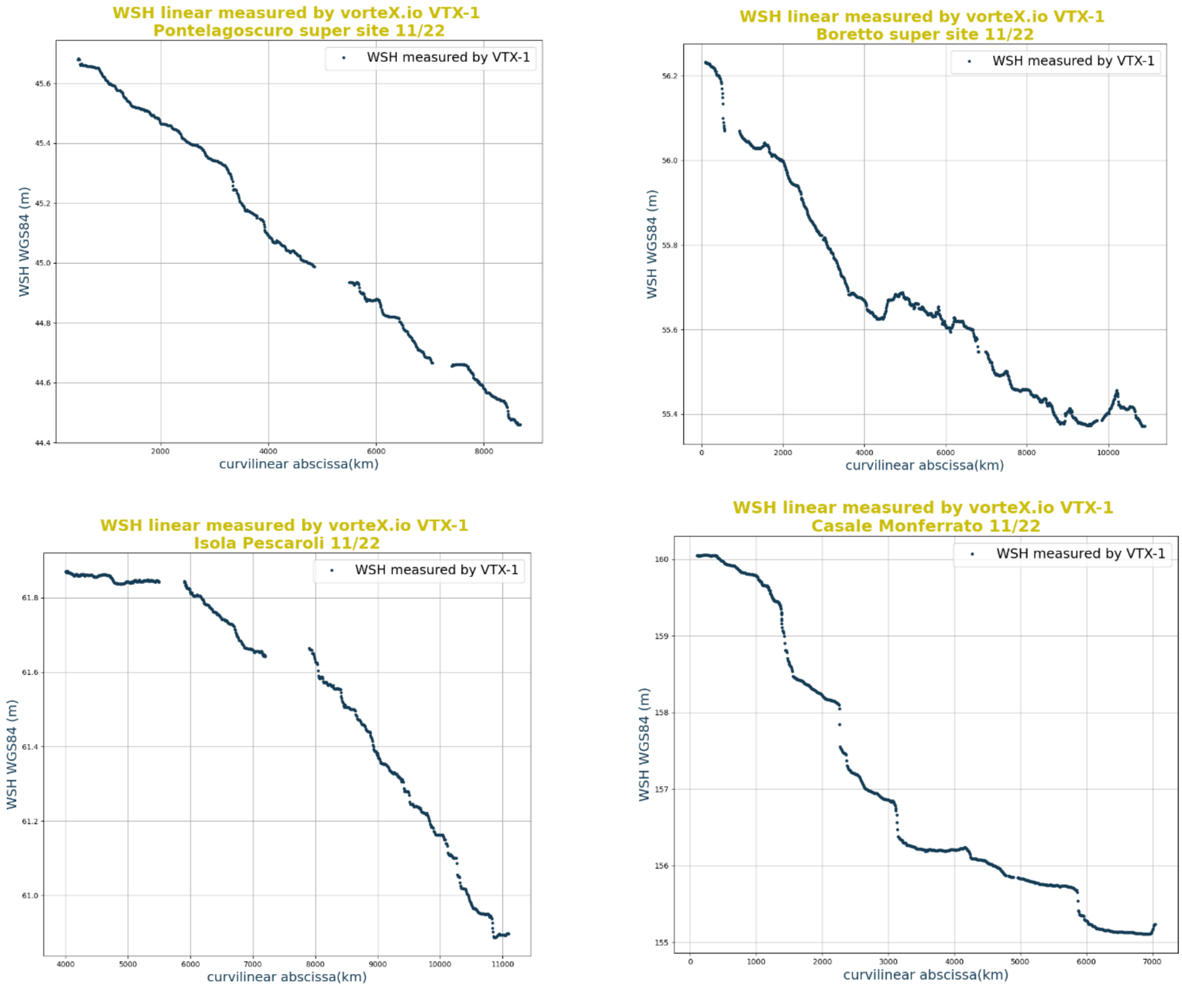


Figure 98: Water surface height profile measured by vorteX.io light altimeter during the campaign on each super-site

The results of this campaign are very different depending on the super-sites. On “Casale Monferrato” and “Pontelagoscuro” super-sites the quality of data is excellent, and the topography measurements are very precise with little noise. On “Boretto” super-site, the topography measurement is noisier than in the 2 other super-sites, especially on the second part of the slope measurement. This noise is due to a high altitude of flight, because of the vegetation on the riverbanks, and also due to the river roughness. The Po River was at low water and without current, the water surface was extremely smooth, almost like a mirror. In this condition a higher flying altitude results into less back-scattered signal. On “Isola Pescaroli” super site we faced the same phenomenon. Even with this noise, the quality of the measurements is good enough to compute FRM.

7.2 Computing FRM on the Po River

7.2.1 Computing the FRM

On the Po River there are 4 different “super sites”, each site has different characteristics. On 3 super-sites, Sentinel-3A and Sentinel-3B ground tracks are present. On the last site (“Boretto”), there is only a Sentinel-3A ground track. As mentioned in the TD-6 [RD6], a super site can be in 2 different complexity classes depending on the geometry of the satellite ground tracks. Following the Cal/Val site classification detailed in the TD-6 document (RoadMap) [RD6], the “Isola Pescaroli” site corresponds to a complexity level 0 site for Sentinel-3B and correspond to a complexity level 3 site for Sentinel-3A. The 3 other super sites correspond to complexity level 3 sites for both Sentinel-3A and Sentinel-3B.

Along with the Micro-Stations, the super sites are also equipped with sensors belonging to the Italian network that is managed by the AIPo agency over the Po basin. In the following, the FRM of the existing network is also computed to have a larger view in time with respect to the recent installation of the Micro-Stations.

Complexity level 0 site:

As mentioned before the "Isola Pescaroli" super-site corresponds to a complexity level 0 site for Sentinel-3B. The in-situ sensor is installed just under the satellite ground track. The computation of the FRM is very simple: there is no slope to be accounted for, no other in-situ data required, the measurement of the in-situ sensor can be performed at the exact same time as the satellite passes. The FRM corresponds to the measurement of the vorteX.io Micro-Station that has been configured to perform a measurement at the exact time of the Sentinel-3B pass for the ground track #158. The Equation of the FRM on this site is:

$$\boldsymbol{WSH_{FRM}(t) = WSH_{IS}(t)}$$

Complexity level 3 sites:

As mentioned before all the other sites on the Po River correspond to complexity level 3 sites. The in-situ sensors are not installed just under the satellite ground tracks. First, we need additional in-situ data to compute the time lag between the virtual station and the in-situ sensor. The Micro-Station will perform its measurement at $\boldsymbol{t + \delta_t}$. The topography of the Po River is complex, we need to take into account the slope. The FRM corresponds to the measurements of the vorteX.io Micro-Stations that have been configured to perform a measurement at the exact time $\boldsymbol{t + \delta_t}$ corrected from the slopes measured by the moving sensors. This slope topography must be corrected from the evolution of the water level during the campaign. The Equation of the FRMs on these sites is:

$$\boldsymbol{WSH_{FRM}(t) = WSH_{IS}(t + \delta_{ts}) + \left(\Delta WSH_{slope} - Corr_{evo\_tempo}\right)}$$

with $\boldsymbol{\Delta WSH_{slope} = WSH_{moving\_sensor\_at\_SGT} - WSH_{moving\_sensor\_at\_IS}}$

and where $\boldsymbol{WSH_{moving\_sensor\_at\_IS}}$ corresponds to the moving sensor measurement next to the in-situ sensor and

$\boldsymbol{WSH_{moving\_sensor\_at\_SGT}}$ to the moving sensor measurement at the actual position of the satellite ground track. $\boldsymbol{Corr_{evo\_tempo}}$ corresponds to the correction related to the spatial and temporal evolution that we apply on the moving sensor measurements to correct the water level evolution of the river during the campaign time.

Prerequisites:

All the sites in Italy are at least complexity level 3 super sites. The next prerequisites can be applied on each site. "Isola Pescaroli" is a complexity level 0 super site; no prerequisites are needed on this site to compute FRM for the Sentinel-3B ground track.

1. The centreline

A river centreline is needed for the FRM processing on the "Po River". This centreline is computed from a kml file built from a Google Earth trajectory, there are no precise centreline database easily accessible in Italy. The centreline is the curvilinear abscissa along the river. The computed centreline on the "Po River" on each site is shown in Figure 99.

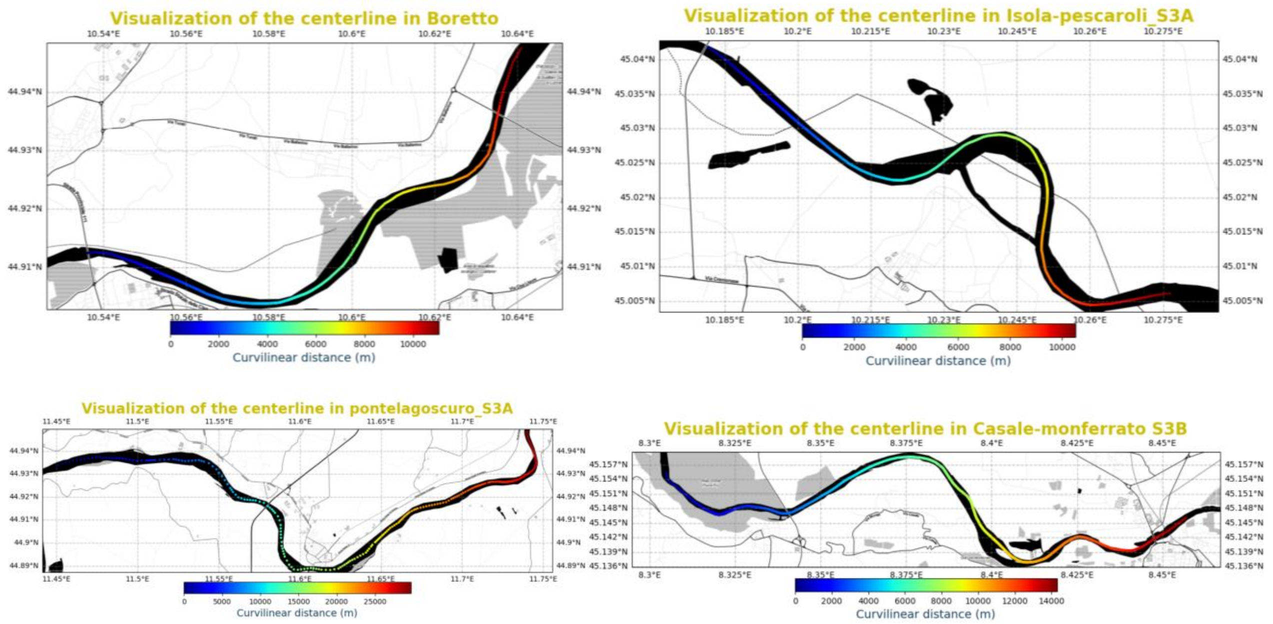


Figure 99: Visualisation of the centreline on each site on the "Po River"

2. River topography measurements

As mentioned before, a drone campaign has been performed on each site to measure the river profile. The campaign was performed between the 07/11/2022 and the 10/11/2022. The measured river profiles are shown in Figure 98. The river topography measurements must not be corrected because the campaigns were very fast and because the Po River was characterized by low flow regime.

3. Compensate the river profiles measured during the drone campaigns from the water level evolution

7.2.2 Comparison with Sentinel-3

This exercise has been performed by IRPI team. The FRM is computed as described in the TD-6 document [RD6].

FRM Processing:

1. Load Sentinel-3 data and get the actual time *t* and location of the satellite measurements.

Sentinel-3 data are downloaded from the ESA Copernicus Open Access Hub (https://scihub.copernicus.eu/). The Figure 100 illustrates data from cycle 89 on the S3A ground track 79.

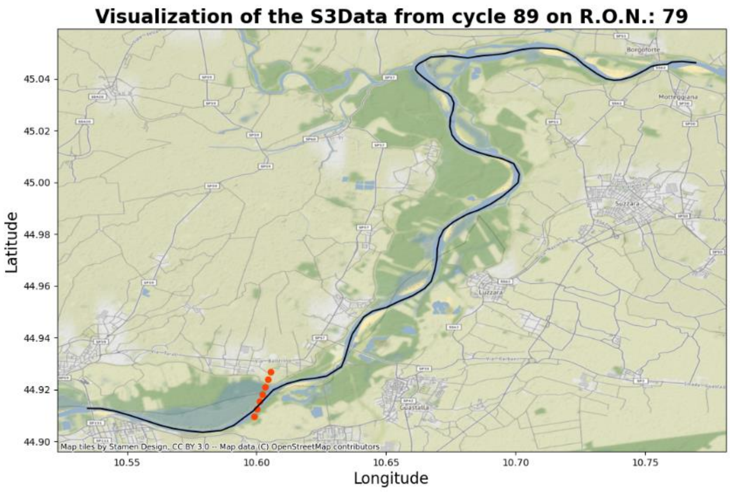


Figure 100: Map showing the positions of the S3A measurements on cycle 89 track #79 over the Po River

2. Compute the propagation time ***δt***

The propagation time and the associated average flow speed are computed on this area and at the time of the satellite pass using the Micro-station installed at Boretto and the AIPo station existing at Borgoforte section. On this example the propagation time is 10800 s between the two stations which are approximately 32 km apart with an average speed of 2.96 m/s. The propagation time δ_t between Boretto Micro-Station and the selected satellite track is 1481s (less than half an hour).

3. Compute the height at the reference station at ***t + δt***

The ellipsoidal height measured by the Boretto Micro-Station at ***t + δt*** is selected (or interpolated if the time does not correspond exactly, i.e. less than 1 minute).

4. Finally, the FRM value is computed combining the height at the reference station at ***t + δt***.

The comparison between FRM value and the Sentinel-3A measurement for cycle 86 is shown in Figure 101.

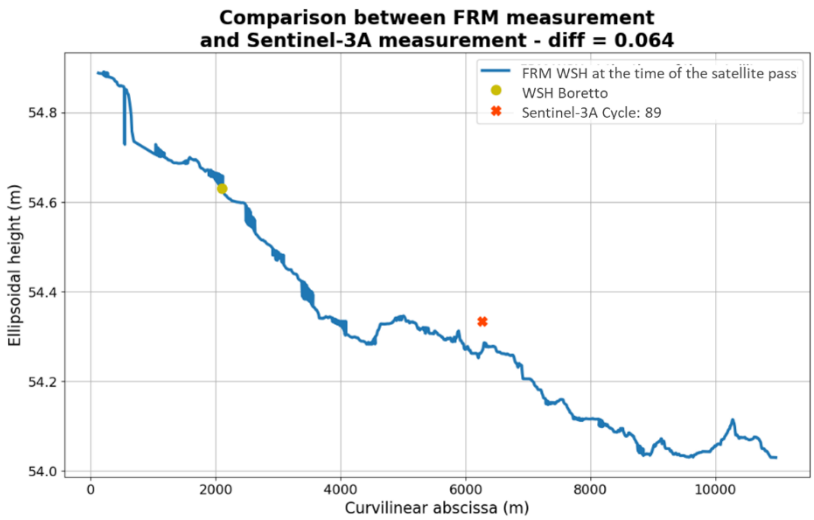


Figure 101: Comparison between the FRM measurement and the Sentinel-3 measurement in Boretto for cycle 89. The red cross corresponds to the Sentinel-3 water surface height (w.r.t. reference ellipsoid), the yellow dot corresponds to the measurement of the Boretto Micro-Station at *t+δt*, and the blue line is the river profile added to the Micro-Station measurement to symbolize the FRM measurement.

“Boretto” super-site:

The performance indices obtained on the comparison between the FRM of Micro-Station on the “Boretto” super-site and Sentinel-3A data are about of **0.17 m** in terms of **RMSE** and **0.14 m** in terms of **average error** (Figure 101).

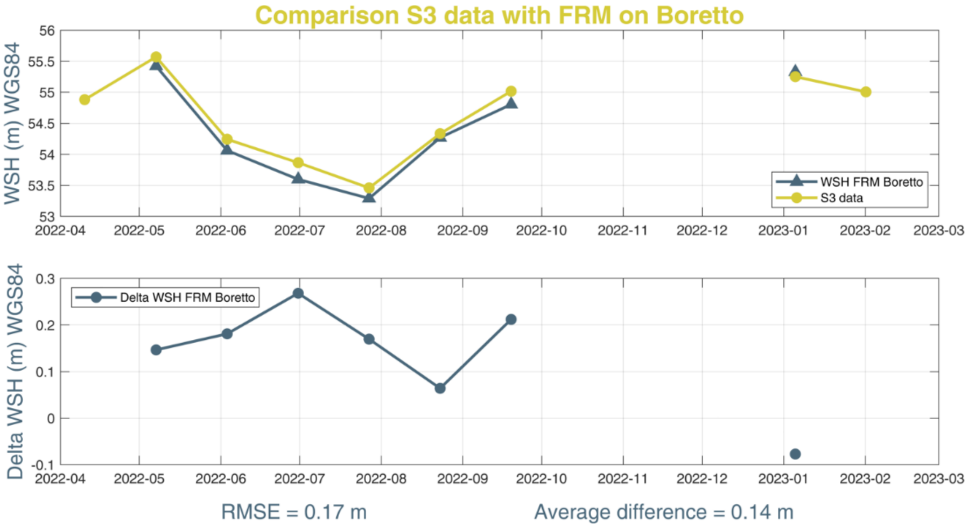


Figure 102: Comparison between FRM Micro-station and Sentinel-3A measurements on the Boretto site on the several cycles

To increase the number of comparisons, we have extended the date when the in-situ data was available by using an existing in-situ sensor of the AIPo network located next to the micro-station. The altimetric reference of this sensor was not good and we used the measurements of the micro-station to set the exact altitude of this sensor. We do not own this sensor and we have no idea about its accuracy and drift. The comparison shown in Figure 103 confirms the good agreement between the satellite and the ground data that in this case is from AIPo network with **RMSE of about 0.24 m** and **bias of -0.12 m.**

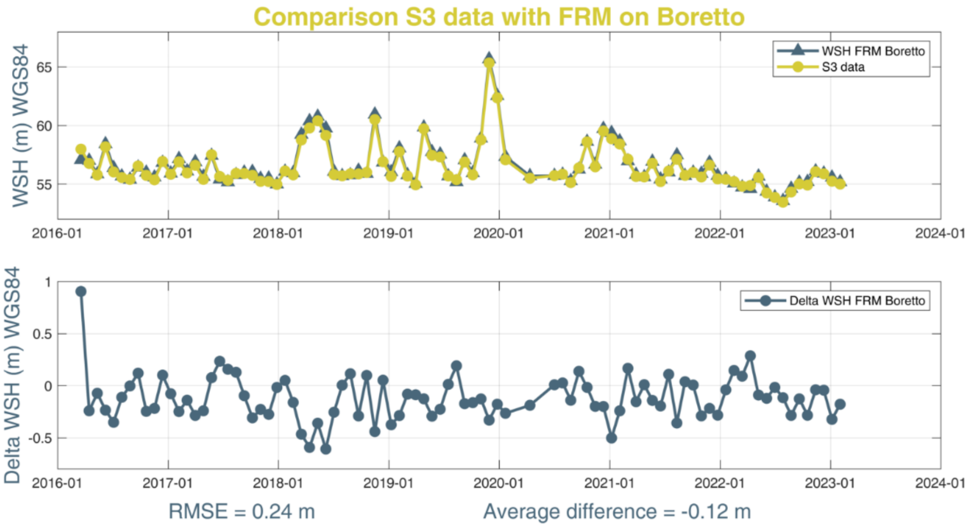


Figure 103: Comparison between ground measurements from Italian Network (AIPo) and satellite measurements from Sentinel-3A track 79 in Boretto

“Casale Monferrato” super site:

The comparison between FRM of Micro-Station and Sentinel-3A and Sentinel-3B for the site of Casale Monferrato is illustrated in Figure 104 and Figure 105, respectively. The figures show the big differences due to the regime that changes from the location of the track of satellite (upstream of the weir) and the FRM that is located between two weirs.

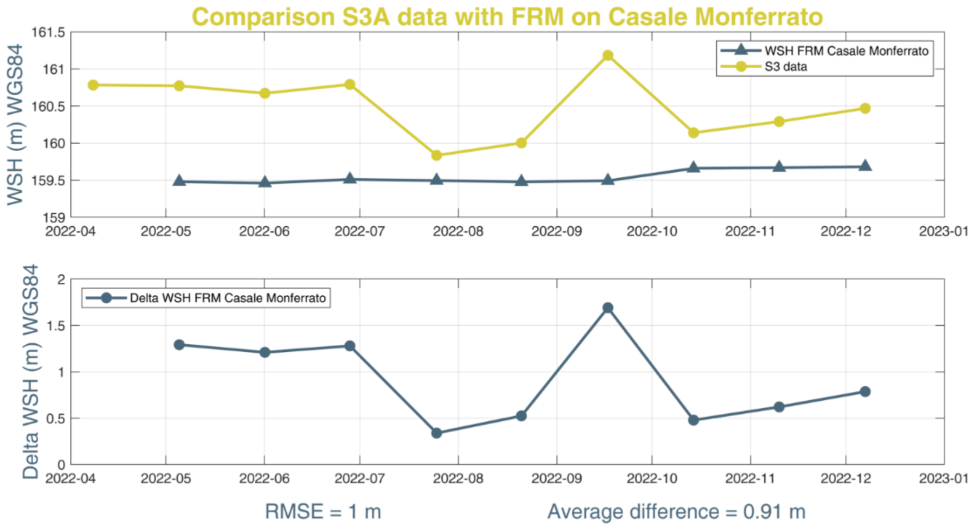


Figure 104: Comparison between FRM Micro-station and Sentinel-3A measurements on the Casale Monferrato site on several cycles

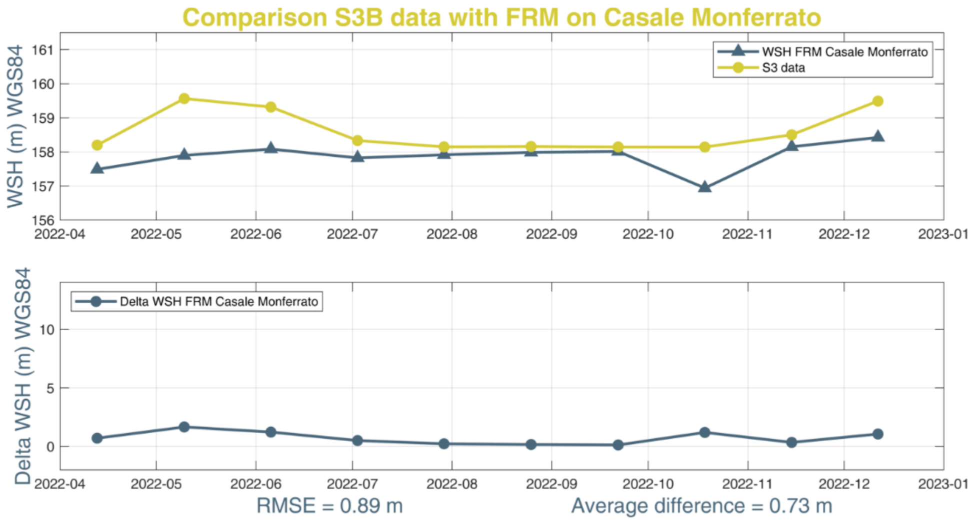


Figure 105: Comparison between FRM Micro-station and Sentinel-3B measurements on the Casale Monferrato site on several cycles

By analysing a longer period through the comparison with the AIPo station it is evident a constant value after April 2020, due to the building of a weir downstream the hydro-monitoring gauge that blocks the flow storing a certain volume of water. The flow observed by satellite is not affected by the weir and it shows still variation after April 2020 as illustrated in Figure 106. Figure 107 shows the comparison with respect to the satellite S3B data with FRM and in this case it seems that the flow is quite stable except for the outliers (value above 165 m) that clearly need to be filtered.

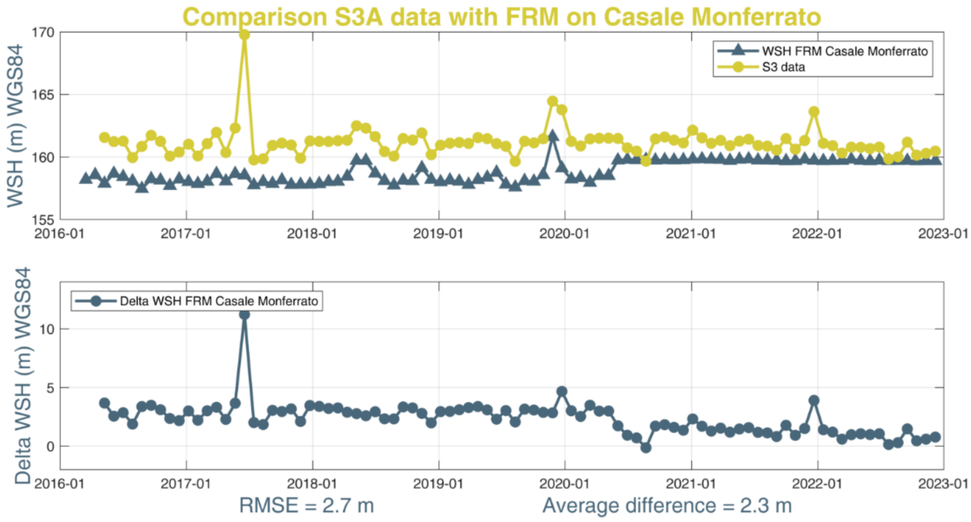


Figure 106: Comparison between ground measurements from Italian Network (AIPo) and satellite measurements from Sentinel-3A track 42 in Casale Monferrato

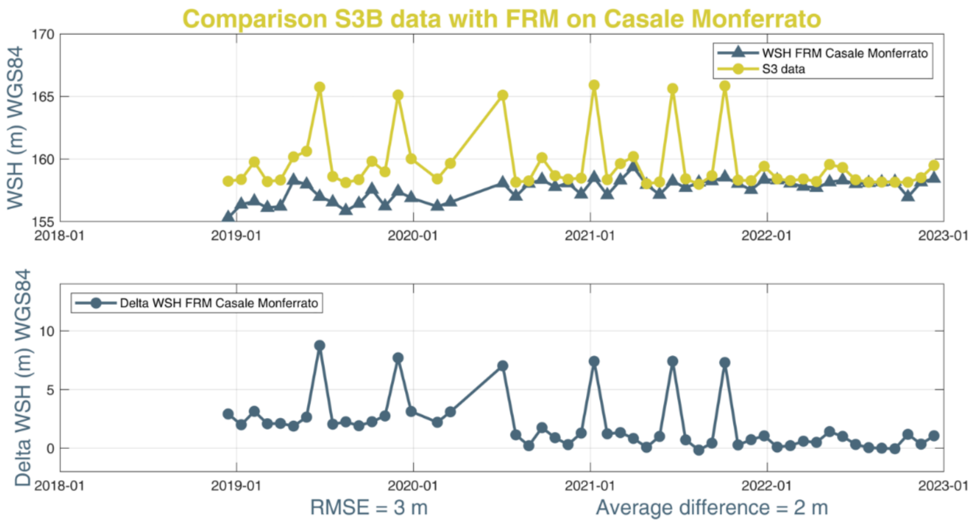


Figure 107: Comparison between ground measurements from Italian Network (AIPo) and satellite measurements from Sentinel-3B track 350 in Casale Monferrato

Because of these results, the best solution is to move the Micro-Station upstream the weir, to be consistent with the flow and with the satellite observations.

<u>“Isola Pescaroli” super site:</u>

Concerning the supersite at Isola Pescaroli the comparison is carried out at Level 0 between the Micro-Station and the Sentinel-3B track, and at Level 3 between the Micro-Station and the Sentinel-3A track. Figure 108 and Figure 109 illustrate the comparison in both stations. The comparison at Level 0 has an **error of 0.23 m** on average and **RMSE** of about **0.47 m**. The big error is in the first point of the WSH FRM. If we remove this first point the performances are **0.18 m of RMSE** and **0.11 m of average error**. In case of comparison with Sentinel-3A at Level 0 the **RMSE** is about **0.36 m** and the average difference is **–0.35 m** indicating always a negative bias.

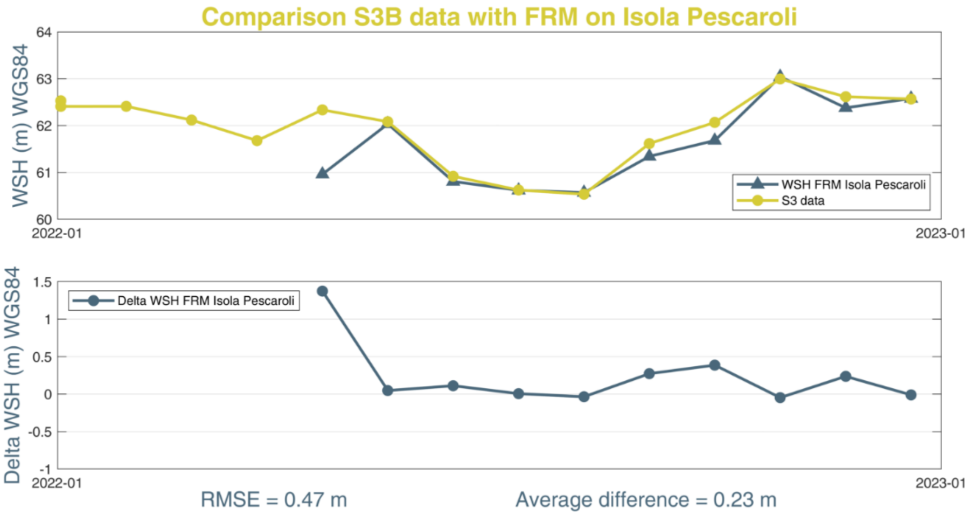


Figure 108: Comparison between FRM Micro-station and Sentinel-3B measurements on the Isola Pescaroli site on several cycles

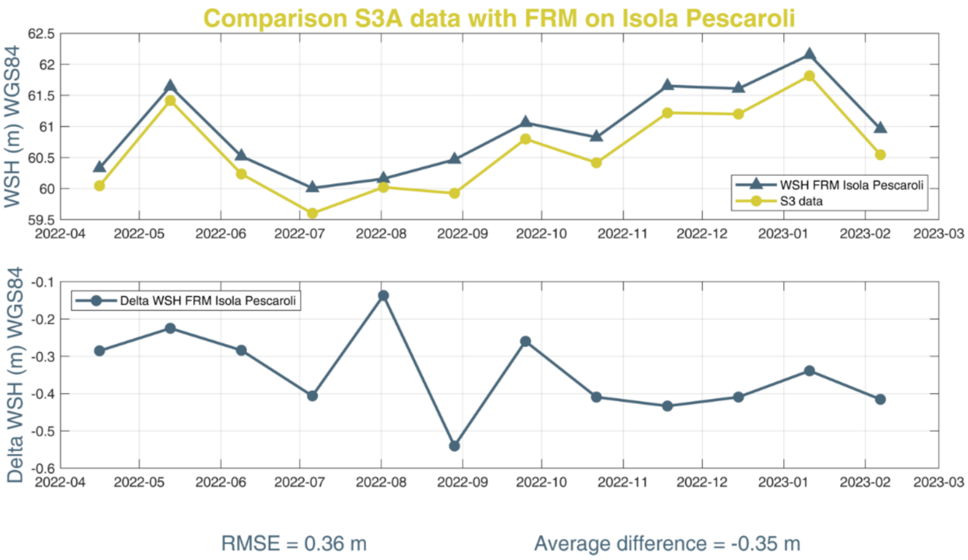


Figure 109: Comparison between FRM Micro-station and Sentinel-3A measurements on the Isola Pescaroli site on several cycles

We assume that the bias observed by the comparison with the virtual station on the Sentinel-3A ground track is due to the quality of the drone measurements. In Isola Pescaroli we struggled to get a perfect drone campaign and we assume that another moving sensor campaign will improve the results.

As on the previous site, the time period to compute comparison has been extended by using AIPo sensor as reference to compute FRM. This analysis in Isola Pescaroli, illustrated in Figure 107, shows a very good agreement between the AIPo and Sentinel-3A (distance of about 10 km) except for an outlier that decreases the performance of the comparison. If such outlier is removed the performance increases at **0.50 m of RMSE** and **0 in terms of bias**. The comparison with the Sentinel-3B located very close to the AIPo station and illustrated in Figure 111, shows **a positive bias of about 68 cm** and **RMSE of 0.89 m**.

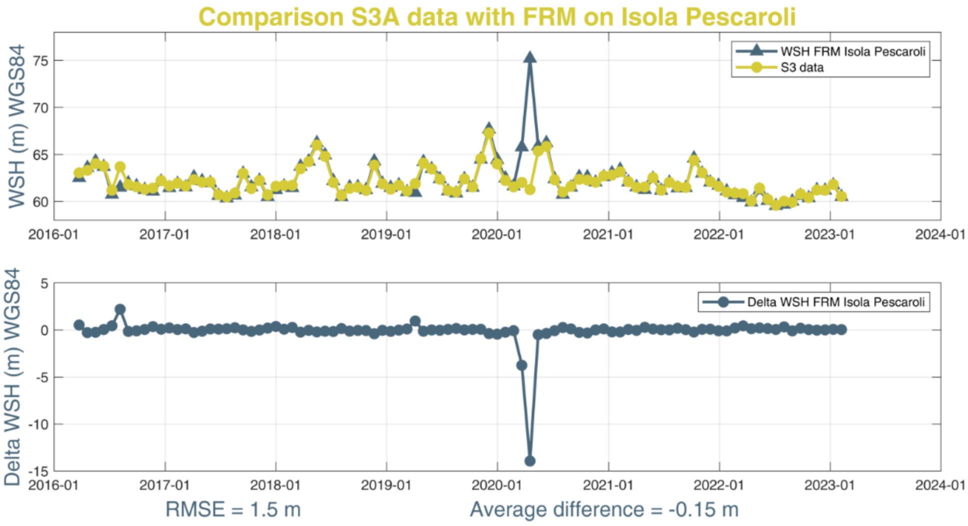


Figure 110: Comparison between ground measurements from Italian Network (AIPo) and satellite measurements from Sentinel-3A track 156 in Isola Pescaroli.

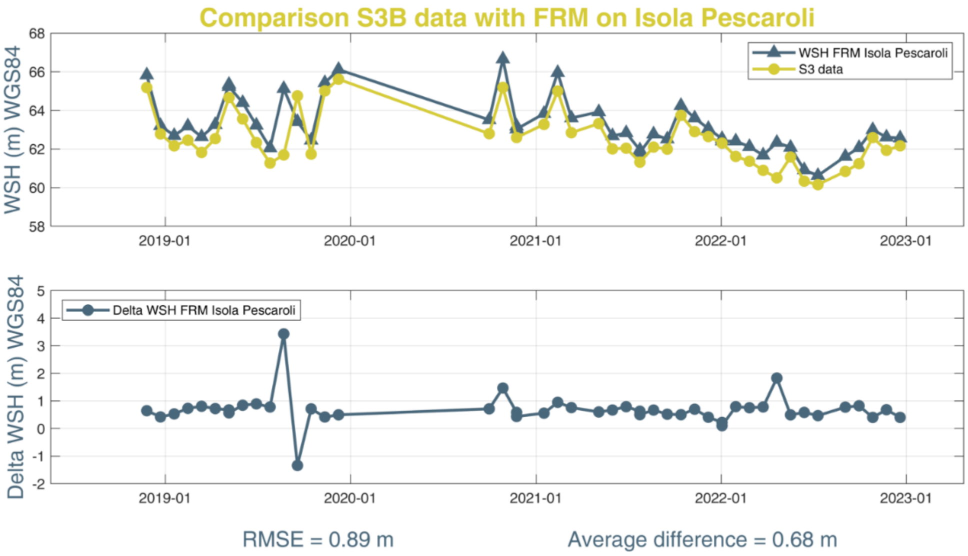


Figure 111: Comparison between ground measurements from Italian Network (AIPo) and satellite measurements from Sentinel-3B track 79 in Isola Pescaroli.

<u>"Pontelagoscuro" super-site:</u>

At the supersite of Pontelagoscuro both the comparisons are at Level 3, and they are related to the Sentinel-3A located upstream the Micro-Station and Sentinel-3B located downstream. As mentioned before, due to external perturbation on the GNSS measurements, half of the river topography measured during the drone campaign was not usable. This half of the topography corresponds to the slope between the micro-station and the Sentinel-3B ground track. Therefore, the comparisons between Sentinel-3B data will not be performed.

Figure 112 shows the comparison between the Sentinel-3A upstream station and the Micro-Station with a **RMSE of 0.19 m** and an **average difference less than of 0.01 m**.

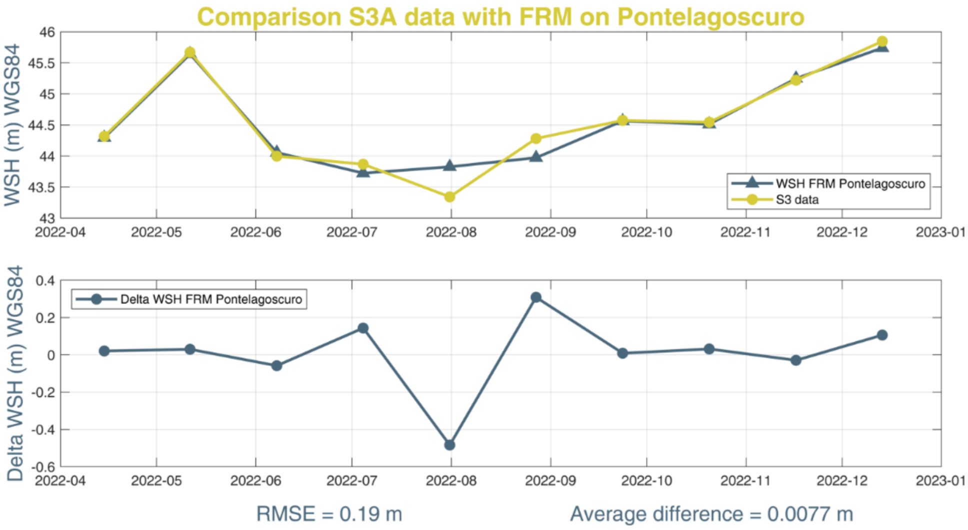


Figure 112: Comparison between FRM Micro-station and Sentinel-3A measurements on the Pontelagoscuro site on several cycles

We applied the same method to increase the date range to perform comparison on this super site. Figure 113 shows the comparison with the upstream Sentinel-3 track 136 and the ground measurements by using AIPo measurements as reference to compute the FRM. No bias exists between the station and the satellite measurements, but some discrepancies are evident especially in 2017 and the beginning of 2018.

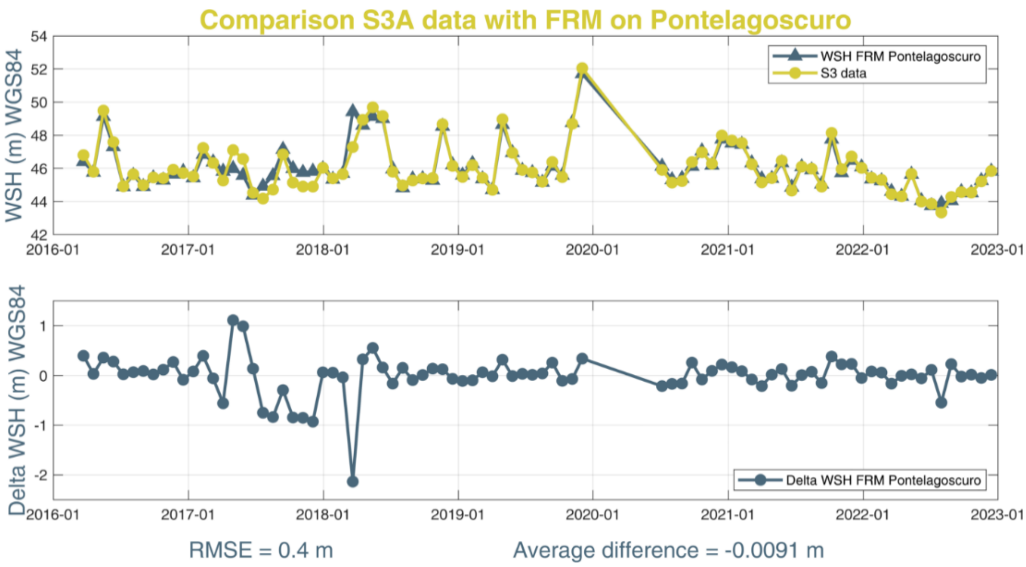


Figure 113: Comparison between ground measurements from Italian Network (AIPo and VorteX.io) and satellite measurements from Sentinel-3A track 136 in Pontelagoscuro

7.2.3 Conclusion on the Po sites

The analysis over the Po River shows very good results in general. Some adjustments are necessary to remove outliers in the satellite time series. For super sites of Boretto, Isola Pescaroli and Pontelagoscuro, both FRM, from Micro-station and AIPo sensor, show a good agreement with the satellite confirming the good quality of the sensors and the procedure defined in TD-6 [RD6]. In Casale Monferrato the building of the weir between the stations and the satellite tracks affected the analysis and, in this case, it is strongly recommended to move the Micro-Station sensor further upstream closer to the satellite tracks.

The Po sites demonstrate also the necessity to perform river profile measurements at 3 different water levels (low, medium, and high). The Garonne site has demonstrated the value added of having such information especially with the FRM processing proposed in the TD-6 [RD6].

These sites should be maintained in the future (after moving the Casale Monferrato station upstream) to meet the long-term requirement of the MPC.

8 The Tiber River

8.1 Campaign performed on the site

On the "Tiber River" we performed a campaign to install 3 in-situ sensors on 3 different "super sites": "Umbertide", "Pierantonio" and "Deruta". In the framework of the St3TART project we planned to install a micro-station on a fourth super-site in "Santa Lucia". Unfortunately, the owner of the bridge has planned a complete refection of the bridge in the month following the planned installation date, and the station would have been removed if we had installed it. We are waiting for the end of the refection to install the micro-station on this super-site. We will not perform the comparison with Sentinel-3 data during this part of the project. These sites have been chosen because the Tiber River is a waterbody with a strong dynamic, narrower than the other river equipped in the framework of the project. A Sentinel-3B ground track crosses the Tiber River near the locations where we installed the Micro-Stations. These sites are therefore ideal cases to evaluate the best possible performances that can be achieved by Sentinel-3. The 3 Micro-Stations are installed under bridges over the "Tiber River". Further explanations on the choice of these sites are given in the TD-6 document [RD6]. The full campaign is described in the corresponding campaign log [RD17]. The campaign was performed on the 05/01/2023, the time-series are available since this date.

The first step of the data analysis is the computation of the reference height of the Micro-Station from the GNSS measurements recorded by the Septentrio base. This procedure is described in the TD-12 document [RD17]. We performed a GNSS measurement on each site. In the next paragraph we will present the results of the positioning of all the Micro-Stations and a short analysis of the data acquired since the installation.

"Umbertide super site":

The PPP positioning of the base provides excellent results with a median height of **290.438 m (WGS84)** and a standard deviation of **2 cm**. During this GNSS measurement the base tracked **18 satellites** in average. The quality of the GNSS measurement is excellent. The rope access technicians have measured a vertical distance between the Micro-Station and the centre of phase of the GNSS base of **1.877 m**. It results in a reference height for the Micro-Station of **288.561 m** in ellipsoidal height. We have not access to the Italian geoid, so it is impossible to provide measurement in the local geoid at this time.

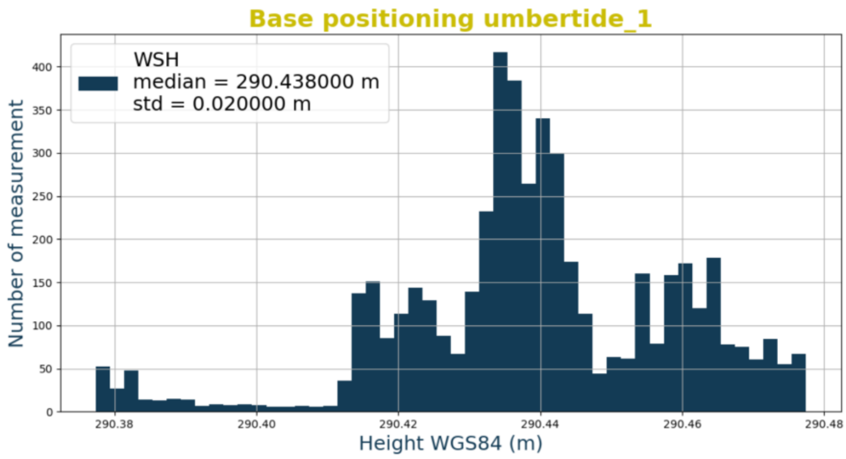


Figure 114: Histogram of the altitudes of the base computed by PPP for "umbertide_1"

The combination of this GNSS processing and the LiDAR measurements provides the precise altitude of the water measured by the Micro-Station. We obtain the time-series measured by the Micro-Station “umbertide_1” (Figure 115).

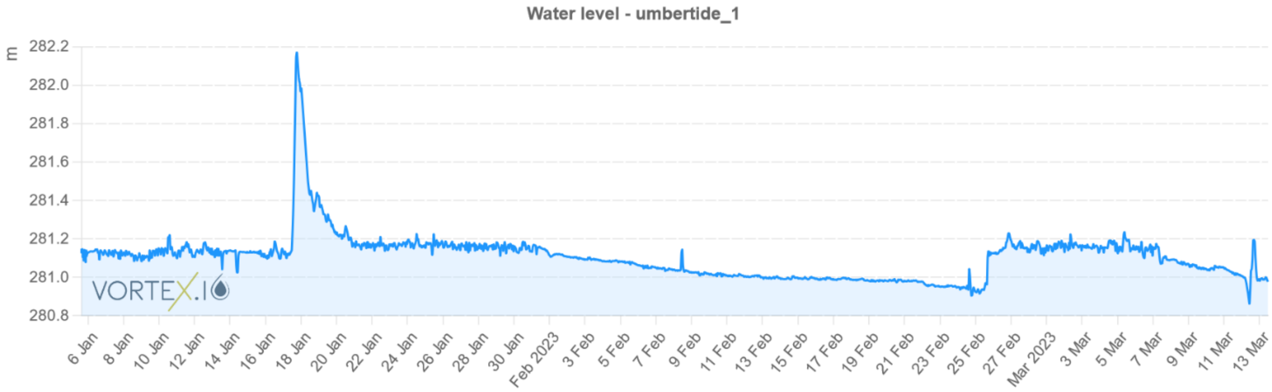


Figure 115: Time series of water surface height measured by the station labelled "umbertide_1" since the installation

The water surface height on “umbertide_1” is quite noisy. On the data we can observe a flood event during the end of January and another one at the end of February. This sensor is installed upstream of a hydrological control. The river is wider at the position of the Micro-station than downstream of the dam. We assume that the noise observed by the micro-station is due to the presence of the dam downstream.

<u>“Pierantonio super site”:</u>

Due to a manipulation error on the base during the GNSS measurement, the GNSS data quality is not good enough to compute the precise positioning of the base and therefore to compute the altimetric reference of the Micro-Station. Another campaign is planned to measure the altimetric reference of “pierantonio_1”. This campaign will be joint with the installation of the Micro-Station in “Santa-Lucia”.

Without a precise GNSS position, only the distance measured by the LiDAR is displayed in the data visualisation platform developed by vorteX.io. We only obtain the time-series of the distance between the Micro-Station and the water surface, “deruta_1” (Figure 116).

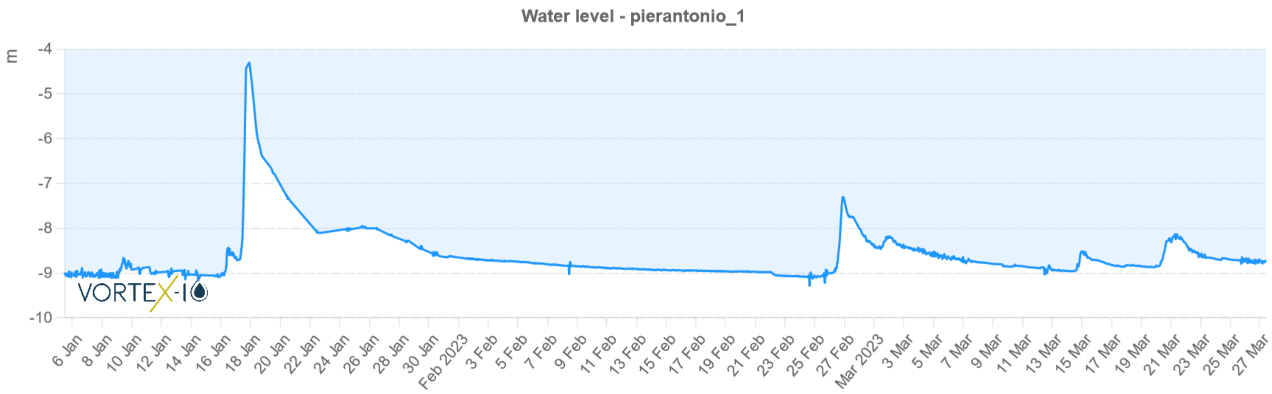


Figure 116: Time series of water surface height measured by the station labelled "pierantonio_1" since the installation

The water surface height on “pierantonio_1” is smoother than in “umbertide_1”. We can observe the 2 flood events monitored by the micro-station upstream. The amplitude of the flood events is larger than in “Umbertide”. We can explain this difference with the topography of the river. The river is wide at Umbertide because the micro-station is located upstream a dam. If the surface is larger the rise of water due to a flood event will be smaller. “Pierantonio” sensor is located after the hydrological control, on a narrower part of the river. The same discharge will result into a greater water level rise.

"Deruta super site":

The PPP positioning of the base provides excellent results with a median height of **217.495 m (WGS84)** and a standard deviation of **1.3 cm**. During this GNSS measurement the base tracked **18 satellites** in average. The quality of the GNSS measurement is excellent. The rope access technicians have measured a vertical distance between the Micro-Station and the centre of phase of the GNSS base of **1.597 m**. It results in a reference height for the Micro-Station of **215.898 m** in ellipsoidal height. We have not access to the Italian geoid, so it is impossible to provide measurement in the local geoid at this time.

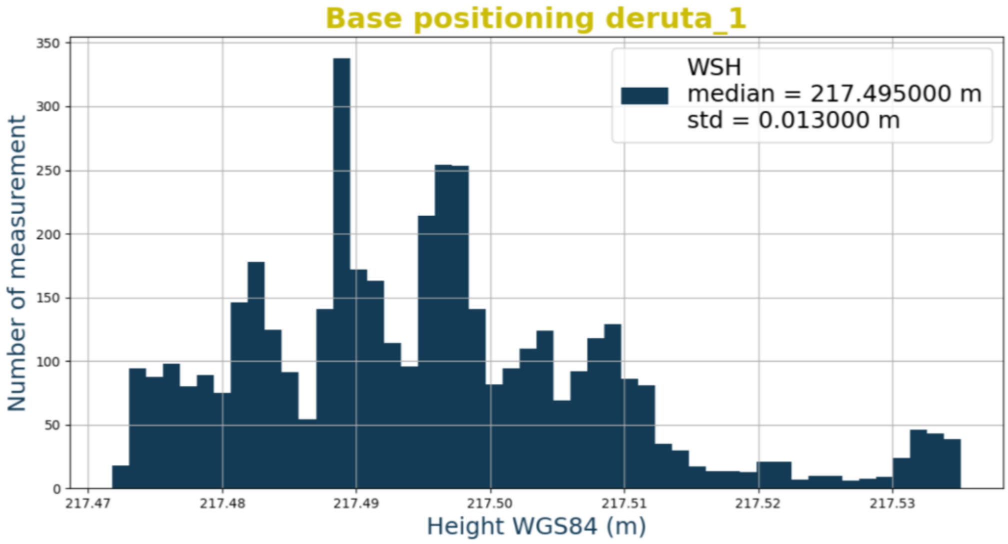


Figure 117: Histogram of the altitudes of the base computed by PPP for "deruta_1"

The combination of this GNSS processing and the LiDAR measurements provides the precise altitude of the water measured by the Micro-Station. We obtain the time-series measured by the Micro-Station "deruta_1" (Figure 118).

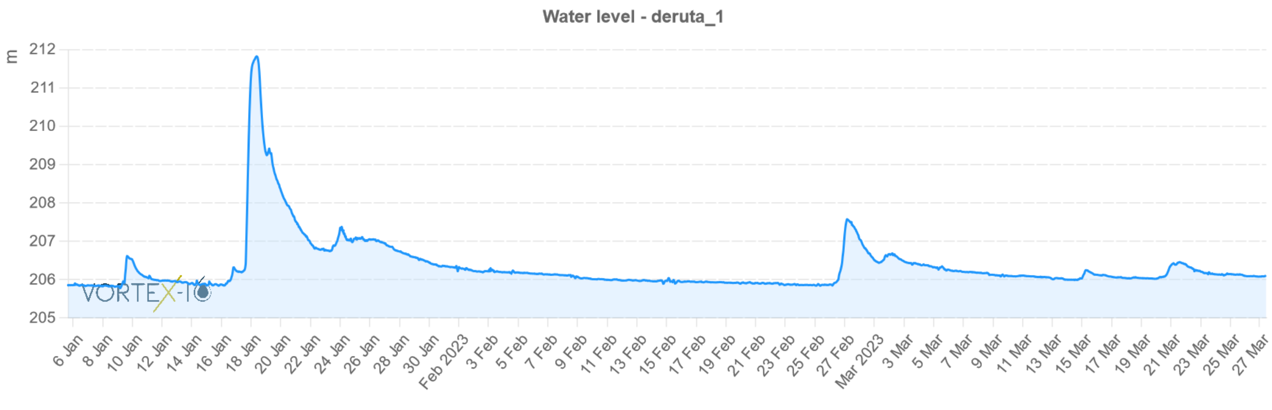


Figure 118: Time series of water surface height measured by the station labelled "deruta_1" since the installation

The water height measured by "Deruta_1" is close to the one measured by Pierantonio if we compare the anomaly. With these 2 stations we can compute the propagation time between the 2 stations. The curvilinear distance between stations is high. There is no hydrological control between the 2 stations, we can observe a big correlation in the water elevation during the flood events. The quality of the data measured by the station "deruta_1" is excellent.

The next figure (Figure 119) enlightens the correlation between the measurements of the 3 Micro-Stations installed on the Tiber River, and the behaviour of the water level due to the hydrological control.

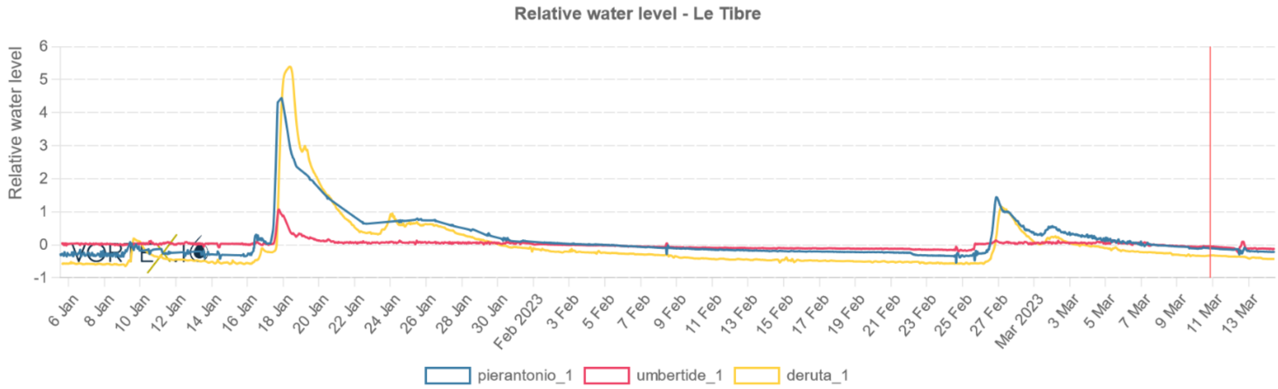


Figure 119: Comparison between the 3 vorteX.io Micro-Station located on the Tiber River

As we can see, the rise of the water level is smaller in "Umbertide" than the one observed by the 2 downstream sensors on both flood events. With the data of these 3 stations, we can compute a time delta between each station. These super sites will be very interesting because we will try to compute a time lag with a hydrological control between 2 Micro-Stations.

8.2 Computing FRM on the Tiber River

8.2.1 Computing the FRM

Following the Cal/Val site classification detailed in the TD-6 document (RoadMap) [RD6], all the sites correspond to complexity level 3 sites, except for "Santa Lucia" site that correspond to complexity level 0. Thanks to the installation of the instrumentation described in the previous paragraph, and following the recommendations related to this site class, we can compute the FRM measurement and then compare to Sentinel-3 data.

Complexity level 0 site:

As mentioned before, the "Santa Lucia" super-site corresponds to a complexity level 0 site for Sentinel-3B. The in-situ sensor is installed just under the satellite ground track. The computation of the FRM is simple: there is no slope to be accounted for, no other in-situ data required, the measurement of the in-situ sensor can be performed at the exact same time as the satellite passes. The FRM simply corresponds to the measurement of the vorteX.io Micro-Station that has been configured to perform a measurement at the exact time of the Sentinel-3B pass for the ground track #541. The Equation of the FRM on this site is:

$$\boldsymbol{WSH_{FRM}(t) = WSH_{IS}(t)}$$

Complexity level 3 sites:

As mentioned before all the other sites on the Tiber River correspond to complexity level 3 sites. The in-situ sensors are not installed just under the satellite ground tracks. First, we need additional in-situ data to compute the time lag between the virtual station and the in-situ sensor. The Micro-Station will perform its measurement at $\boldsymbol{t + \delta_t}$. The topography of the Tiber River is complex, we need to take into account the slope. The FRM corresponds to the measurements of the vorteX.io Micro-Stations that have been configured to perform a measurement at the exact time $\boldsymbol{t + \delta_t}$ corrected from the slopes measured by the moving sensors. This slope topography must be corrected from the evolution of the water level during the campaign. The Equation of the FRMs on these sites is:

$$\boldsymbol{WSH_{FRM}(t) = WSH_{IS}(t + \delta_{ts}) + \left(\Delta WSH_{slope} - Corr_{evo\_tempo}\right)}$$

with $\Delta WSH_{slope} = WSH_{moving\_sensor\_at\_SGT} - WSH_{moving\_sensor\_at\_IS}$

and where $WSH_{moving\_sensor\_at\_IS}$ corresponds to the moving sensor measurement next to the in-situ sensor and $WSH_{moving\_sensor\_at\_SGT}$ to the moving sensor measurement at the actual position of the satellite ground track. $Corr_{evo\_tempo}$ corresponds to the correction related to the spatial and temporal evolution that we apply on the moving sensor measurements to correct the water level evolution of the river during the campaign time.

Prerequisites:

All the sites on the "Tiber River" are complexity level 3 super sites. The next prerequisites can be applied on each site. "Santa Lucia" is a complexity level 0 super site, so there are not prerequisites for this site.

1. The centreline

A river centreline is needed for the FRM processing on the "Tiber River". This centreline is computed from a kml file built from a Google Earth trajectory, there are no precise centreline database easily accessible in Italy. The centreline is the curvilinear abscissa along the river. The computed centreline on the "Tiber River" on each site is shown in Figure 120.

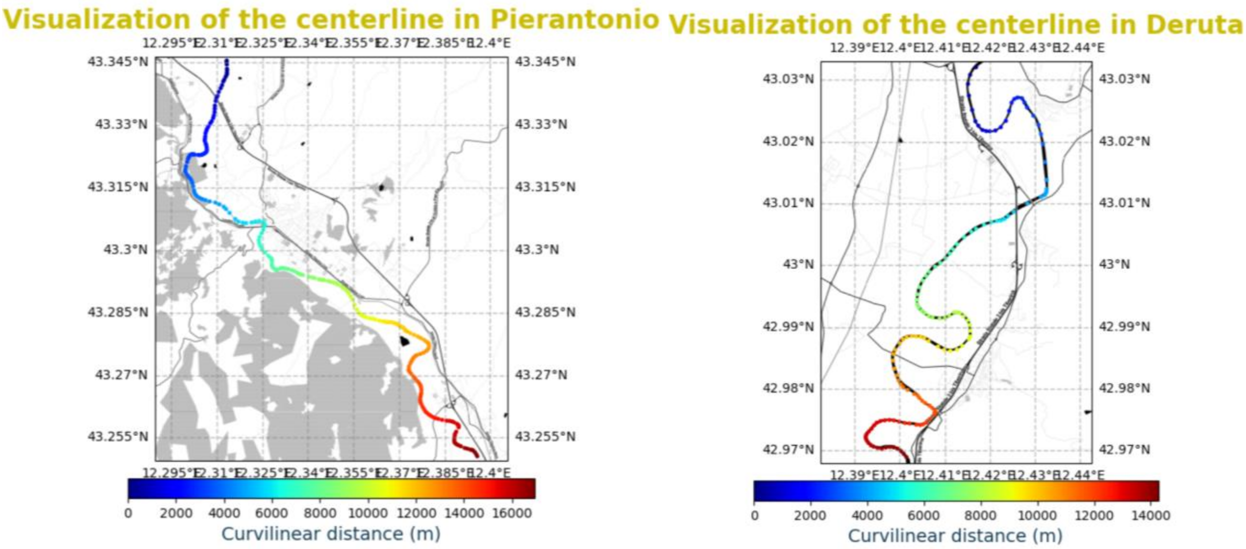


Figure 120: Visualisation of the centreline on the Tiber River

2. River topography measurements

No Moving sensor measurements have been performed on these sites and are planned in the framework of the project. These sites have been identified lately during the project so there was not enough time to perform and process such campaign. The comparison will be performed with an estimation of the slope from IceSat-2 measurements computed by IRPI. In addition, on the "Deruta" super site, the distance between the satellite ground track and the virtual station is around 500 meters so we will also process the data from "Deruta" as a complexity level 0 super site to increase our knowledge on the dependence of the error on the water topography and on the distance to the Micro-Station.

8.2.2 Comparison with Sentinel-3

This exercise has been performed by IRPI. The FRM is computed as described in TD-6 document [RD6]. Over this river sketch IceSat-2 data are not available, probably due to the width of the river that is quite narrow. The drone flights are therefore mandatory. There is a true interest on those sites because of the topography of the river. The comparisons on those sites ("Umbertide" and "Pierantonio") will be performed after the realization of drone flights. The results on the Garonne River proved that there is a true necessity to measure the slope at different water height to provide FRM with a precise accuracy on narrow river with a strong slope.

Due to the recent installation of the sensors along the Tiber River, there are a few cycles to compare the measurements (just 2). Only a preliminary result is shown for Deruta site because the configuration allows to get more intersections across the river (Figure 121 and Figure 122), but further analysis is necessary to draw robust conclusions over the Tiber.

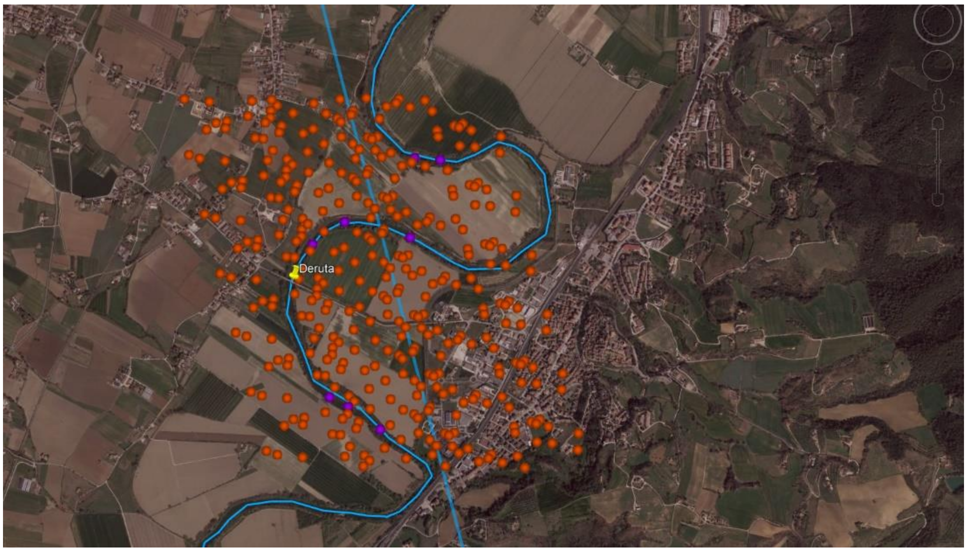


Figure 121: Visualisation of the centreline, the Sentinel-3B measurements (in orange) and the selected track (in violet)

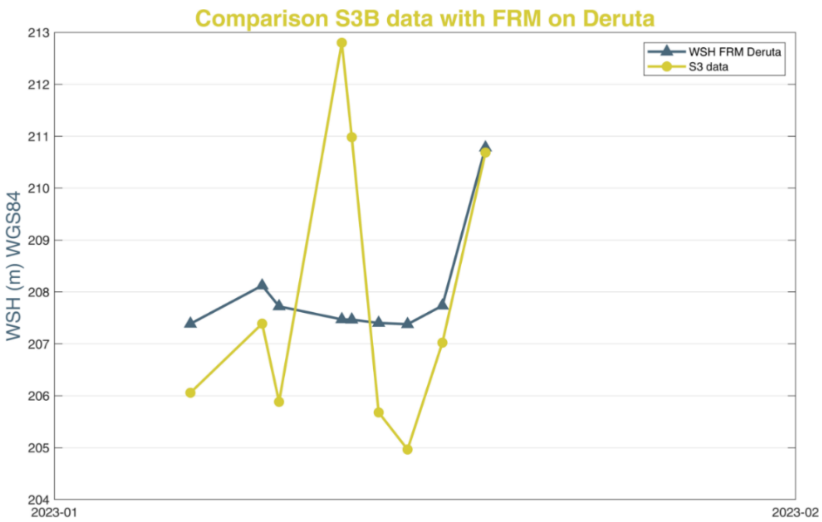


Figure 122: Comparison between the Micro-station measurement at Deruta and Sentinel-3B track #270

The result presented in Figure 122 is a comparison when considering this site as Complexity Level 0 (even if this site has been identified as CL3) because no river profile is available. This result demonstrates the importance of having such river profile and the fact that even if the in-situ sensor is close to the Sentinel-3 track, the strong topography of the site does not allow to provide a good FRM without the slope measurement. This conclusion must be applied also to opportunity sites where we can have in-situ sensor very close to the satellite virtual station but the strong slope of the river does not allow to compute easily a good FRM without the slope measurement.

8.2.3 Conclusion on the Tiber site

The recent installation of the Micro-Stations along the Tiber River does not allow to perform any significant comparison at this stage. However, the first preliminary results for Deruta station are encouraging results. This super site is quite interesting due to the several intersections of the satellite track with the river meanders. Further analyse should be carried out to investigate the effect of the distance of the satellite track from the FRM. The next step is also to install the Micro-station at Santa Lucia as planned but not performed (due to work of local authorities on the bridge).

As the results are encouraging, we recommend to maintain these sites and to perform the appropriate river topography measurement needed to fully exploit these sites.

9 Seine estuary in Honfleur

9.1 Campaign performed on the site

9.1.1 In-situ sensors

On “Honfleur” site we performed a campaign to install an in-situ sensor on the “Seine estuary” under a Sentinel-3A track. This site was chosen because it is an ideal case to evaluate the best possible performances that can be achieved by Sentinel-3 on estuaries sites. The station is installed on a structure above the “Seine River”. Further explanations on the choice of this site are detailed in the TD-6 document [RD6]. The full campaign is described in the corresponding campaign log [RD20]. The campaign was performed on the 02/11/2022, the time-series is available since this date.

The first step of the data analysis is the computation of the reference height of the Micro-Station from the GNSS measurements recorded by the Septentrio base. This procedure is described in the TD-12 document associated with the campaign. The quality of the GNSS measurements made during the installation is not good enough. A new campaign will be performed in the next weeks to measure the altitude of the Micro-Station. To measure the altitude of the Micro-station we used the precise measurements of the water altitude performed by the drone at the exact same time as a Micro-station measurement. This method gave us a precise altitude of **7.493 m (IGN 69)** for the Micro-station.

9.1.2 Moving sensors

The super-site in “Honfleur” is the only super-site in estuary. In order to increase the hydrological knowledge on the super-site a campaign have been performed to measure transect of the Seine River. The transects have been performed near the Micro-station and also upstream and downstream. The water level in Honfleur is impacted by the tides. We performed several times each transect to measure the effect of the tides near the Micro-Station. The campaign is fully described in the corresponding campaign logs [RD19].

In the next paragraph we present the results of the campaign performed by the vorteX.io team in partnership with a drone pilot company I-TECHDRONE. As for the Micro-Stations, the first data analysis we’ll present is the positioning of the geodesic base and the positioning of the altimeter. Then we present the results of the data analysis of the LiDAR measurements. The procedure applied during this campaign is described in the corresponding campaign logs [RD22].

The position of the base is obtained by performing a PPP (Precise Point Positioning) processing. The obtained position of the base is very precise, with a standard deviation lower than **2 mm**, as shown in Figure 123. The number of satellites tracked by the GNSS base during the acquisition time is around **19** in average. The satellites of the GALILEO, GPS and GLONASS constellations are used to perform the positioning. The quality of the positioning is very good. The base position is **51.849 m (WGS84).**

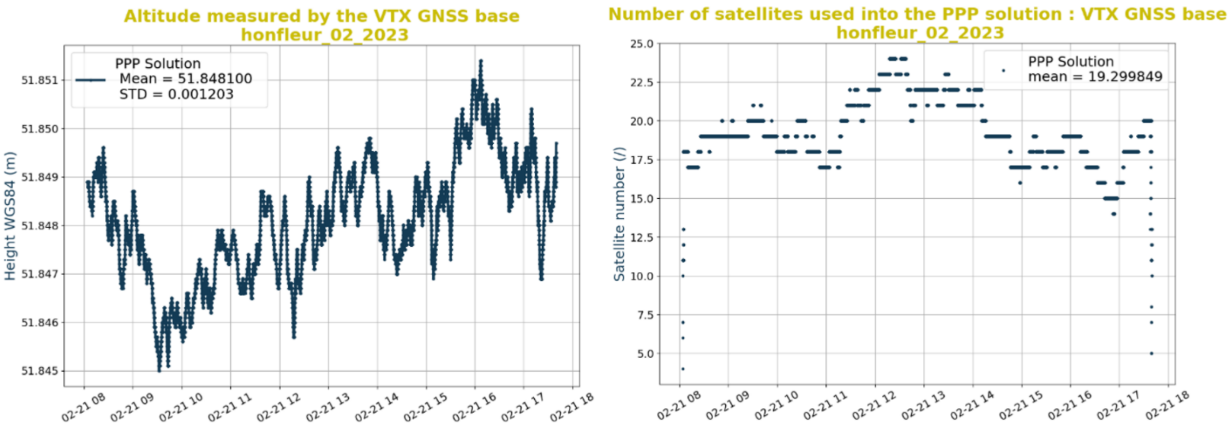


Figure 123: PPP positioning of the base on the left and the number of satellites tracked by the base on the right

Once the precise position of the base is computed, we can perform the PPK positioning of the altimeter for all the flights. All the ambiguities are fixed when the altimeter is flying and thus the positioning is of good quality. We can see in Figure 124 the evolution of the altimeter altitude during the first flight of the campaign. This precise positioning allows to get a precise water surface height measurement.

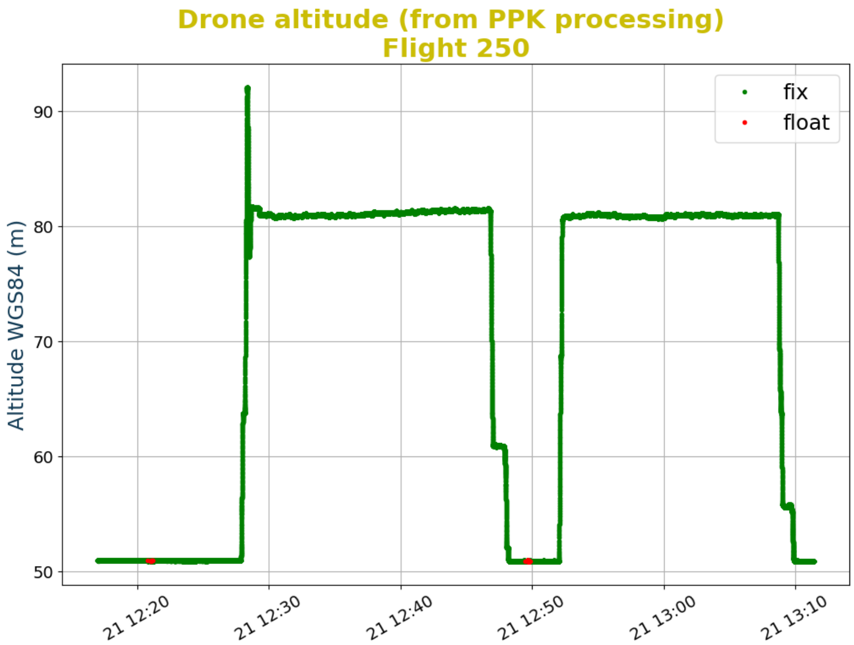


Figure 124: Altitude of the altimeter during the first flight in Honfleur

Once the precise positioning computed, we can compute the water surface height from LiDAR measurements. We have applied a running mean (window of 15 seconds) on the WSH measured by the altimeter to decrease the measurement noise. The LiDAR measurements are performed at 7 Hz, and we finally resampled to 0.5 Hz for the data dissemination.

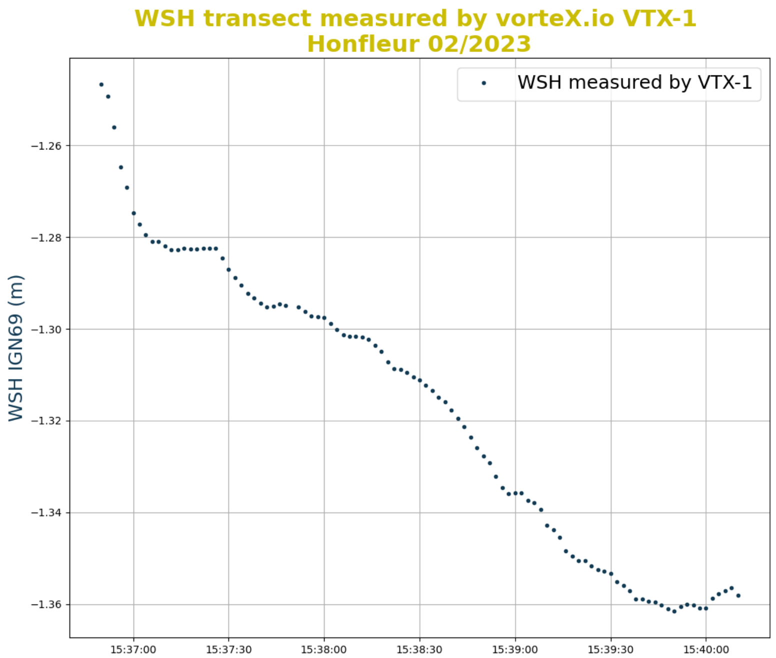


Figure 125: Seine River transect measured by vorteX.io light altimeter during the campaign in Honfleur

The results are excellent. We measure precisely each transects. To perform the measurements the drone went back and forth on the different transects. As shown in the previous figure, we have measured a trend in the data. As presented in the campaign log, due to the presence of fog, the measurements have been performed during the afternoon of the 21st of February. During this date the tide was decreasing as shown in the following graph.

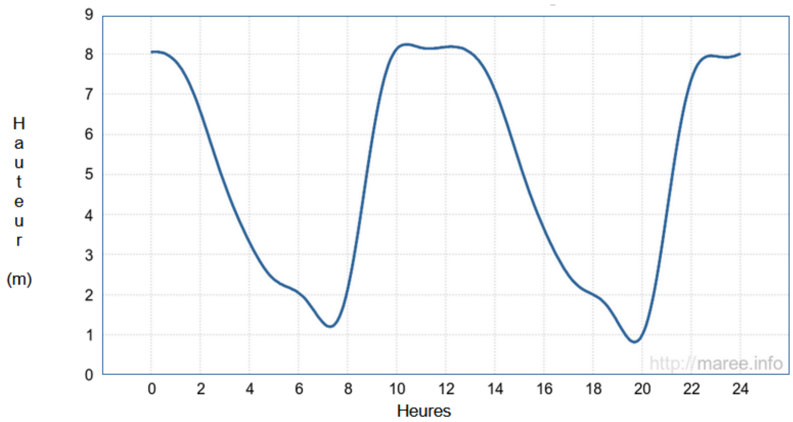


Figure 126: Amplitude of the tide during the 21st of February 2023 in Honfleur

We assume that the trend observed in the measurements is a tidal effect. This trend has been measured during all the afternoon. The speed of the tide seems to change during the day. Further analysis of the data will be performed. These measurements will help to understand the behaviour of the Seine River in the estuary.

9.2 Development of regional high-resolution hydrodynamic model

The complex interactions between the ocean flow and the river flow can produce distortions in the high-frequency variations of the water level measured in estuarian regions, especially in areas strongly influenced by ocean tides. In this context, hydrodynamic models are essential to remove the aliased high-frequency dynamical signals due to the ocean tide and storm surge from the satellite altimetry measurements over estuarine regions, in order to obtain high quality data. In the frame of this project, we developed a high-resolution hydrodynamic model configuration with tide gauge data constraint, in order to simulate the interactions between the river flow and the ocean dynamics in the Seine estuary. This study was carried out with the aim to find the best model configuration and identify potential sources of uncertainties in order to provide accurate water surface elevations for the calibration and validation, or the correction, of satellite altimetry water surface height observations in these areas.

9.2.1 Data and methods

The high-resolution hydrodynamic model employed in this study is the Toulouse Unstructured Grid Ocean model (T-UGOm) developed at the “Laboratoire d’Etudes en Géophysique et Océanographie Spatiales” ([RD29]). In this work we used 3 different bathymetries (Figure 127). The first data set was developed by University of Rouen/LEGOS and used in previous studies ([RD28]). This bathymetry is mainly based on data provided by GIP Seine Aval (https://www.seine-aval.fr/) with a horizontal resolution of 10 m for the mouth region, 5 m upper estuary (from Tancarville to Rouen) and 1 m for the further upriver data along the Seine. The second was the MNT HOMONIM from SHOM ([RD31]) with a resolution of 0.001° (~ 111 m). Finally, we used a blend of the first two reproducing the channel located in front of the port of Le Havre not well represented by University of Rouen/LEGOS bathymetry.

This study was performed using a high-resolution unstructured mesh grid developed by University of Rouen/LEGOS ([RD28]). The grid is resolved with triangular grid elements of 66482 nodes. The horizontal resolution is 4km on the offshore side and 25 m in the lower estuary (Figure 128). A database of tide gauges records was used for upstream boundary conditions, assimilation or validation (Figure 128). Water height time series, from “Balise A” to “Pont de l’Arche” station, were obtained from SHOM http://refmar.shom.fr/fr) over the last 2016-2021 period with a 1-hour sampling interval. In order to make the modelling as realistic as possible, different types of data corresponding to the boundary conditions of the mesh were used. The water height time series at the “Pont de l’Arche” station was used as upstream boundary conditions for the model. Tidal boundary conditions were extracted from the RegAt high-resolution regional tidal model in the North-East Atlantic Ocean ([RD27]).

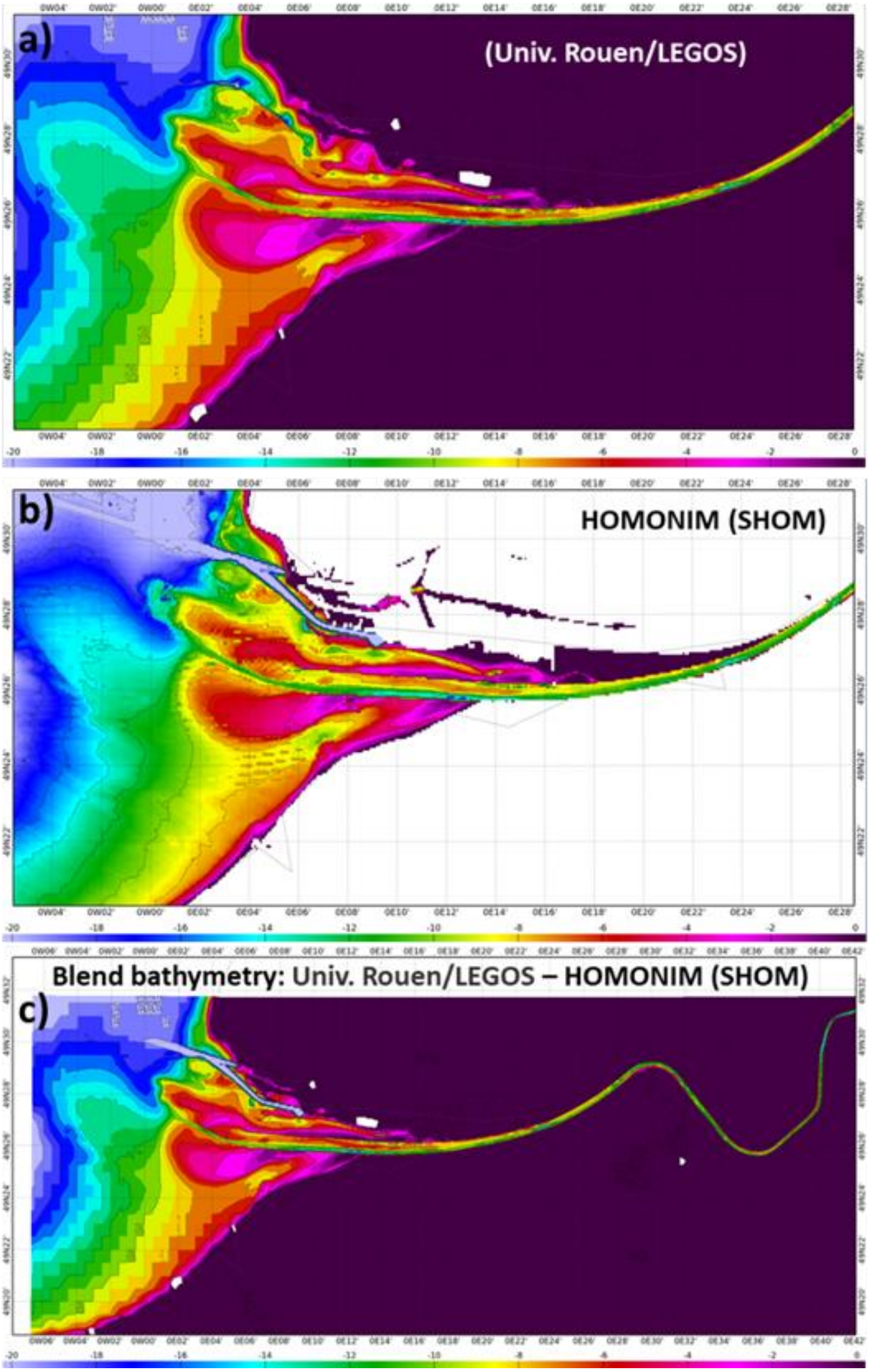


Figure 127: Bathymetries in meters from University of Rouen/LEGOS (a), MNT HOMONIM from SHOM (b) and blended (c).

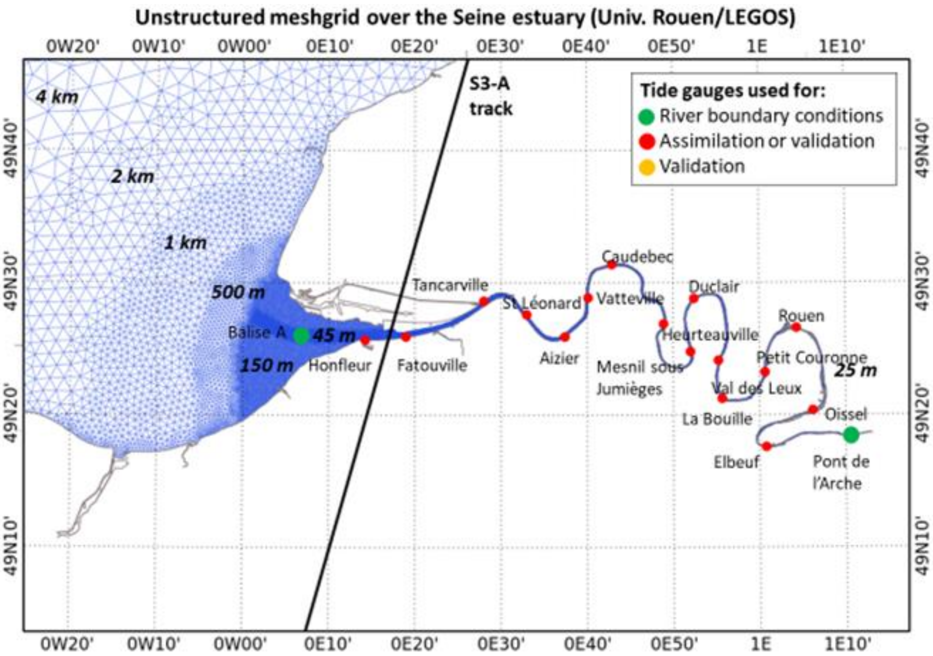


Figure 128: Mesh grid from University of Rouen/LEGOS. Boundary conditions and locations of the Tide Gauge stations. Locations of the Tide Gauge stations used for assimilation/validation are in red points and the upstream river boundary condition (Pont de l'Arche station) is identified by a green point.

9.2.2 Results

9.2.2.1 Free run simulations

Once the mesh-grid, boundaries conditions and the adequate bathymetry were assembled, T-UGOm parameters were calibrated in order to obtain the most accurate hydrodynamic solution. Simulations were performed using the different bathymetric datasets with the aim of improving model realism or to provide useful error compensation. Each resulting simulation was compared to the tide gauge data (Figure 129). The experiences were carried out in June 2017 (30 days).

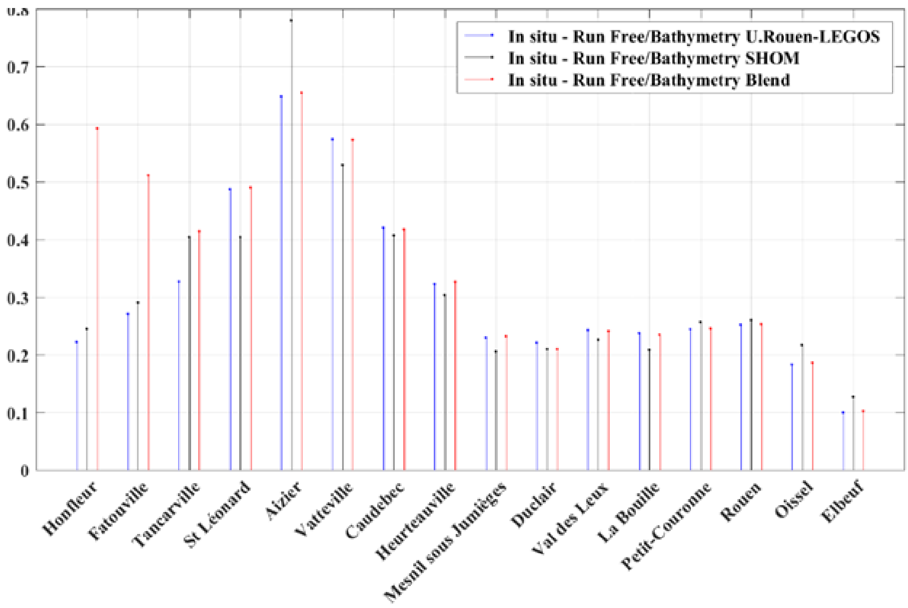


Figure 129: Root-mean-square differences (RMSDs) in meters from in-situ tide gauge data and free model outputs performed with the bathymetries from University of Rouen/LEGOS (blue), MNT HOMONIM from SHOM (black) and blended (red).

The comparison between the root-mean-square differences (RMSD) from in-situ data and the different model output tests indicates no significant improvements in model performance using the SHOM and blended bathymetry. Indeed, a degradation is observed in the "Honfleur" and "Fatouville" stations using the blended bathymetry for the simulations. For this reason, only the bathymetry developed University of Rouen/LEGOS was taken into account for the rest of the simulations. The experiences using the bathymetry developed by University of Rouen/LEGOS showed encouraging results with errors smaller than 40 cm, except in the "Azier" station where we observed errors larger than 60 cm (Figure 129). The time series from in-situ data and model outputs of the Figure 130 show features of the tide interactions and the river flow correctly reproduces the Honfleur station and highlights the differences in the "Azier" station. With the objective of improving the performance of the model around "Azier" station, we made considerable efforts (e.g. significantly increased the grid resolution, accuracy tests with different parameters and GPS carpet) and have not obtained better results over those achieved without degrading solutions downstream or upstream of the estuary.

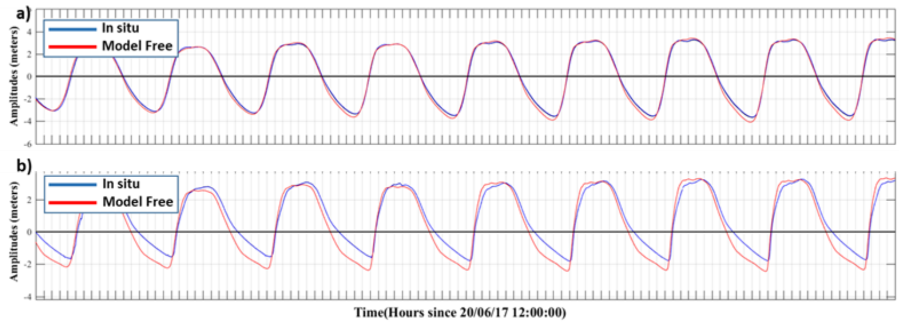


Figure 130: Time series of the surface water elevations (m) for Honfleur (a) and Azier (b) stations. In-situ data is represented in blue and free run model outputs performed with the bathymetries from University of Rouen/LEGOS in red.

9.2.2.2 Tide Gauge Assimilation

The complexity of the interactions between river flow and ocean dynamics in the Seine Estuary requires to locally constrain the model with tidal observations in order to obtain the most realistic simulations possible. We used the tide gauges to constrain the model and sensitivity tests were performed to select the most relevant stations. Several simulations were performed using the model constrained at all tide gauge stations by using different relaxation time scales. The RMSDs obtained with different constraint degrees, ranging from 1 to 300 (r1 to r300) are shown in Figure 131. The comparison of the RMSDs from in-situ data and the different model output tests reveal that the errors of the model constrained with a relaxation time scale of 1 are at least one order of magnitude smaller than free run model outputs.

The water surface elevations from the hydrodynamic model were compared to the Normalized Difference Water Index (NDWI) estimated from Sentinel-2 satellite images. This analysis was performed using 16 clean Sentinel-2 images found during the period 2016-2017. The results have shown a consistency between the water lines calculated by remote sensed data captured by the Sentinel-2 and Model outputs data (Figure 132).

Finally, we assessed the sensitivity of the rest of the assimilated tide gauges. Experiments were performed by constraining the model at all stations (r1) except "St. Léonard", "Heurteauville", "Val des Leux and Oissel". The results showed that when any of the stations is relaxed, the errors increase by 30 cm (Figure 133). These latest findings reveal the crucial role of assimilated data quantity, quality and their locations.

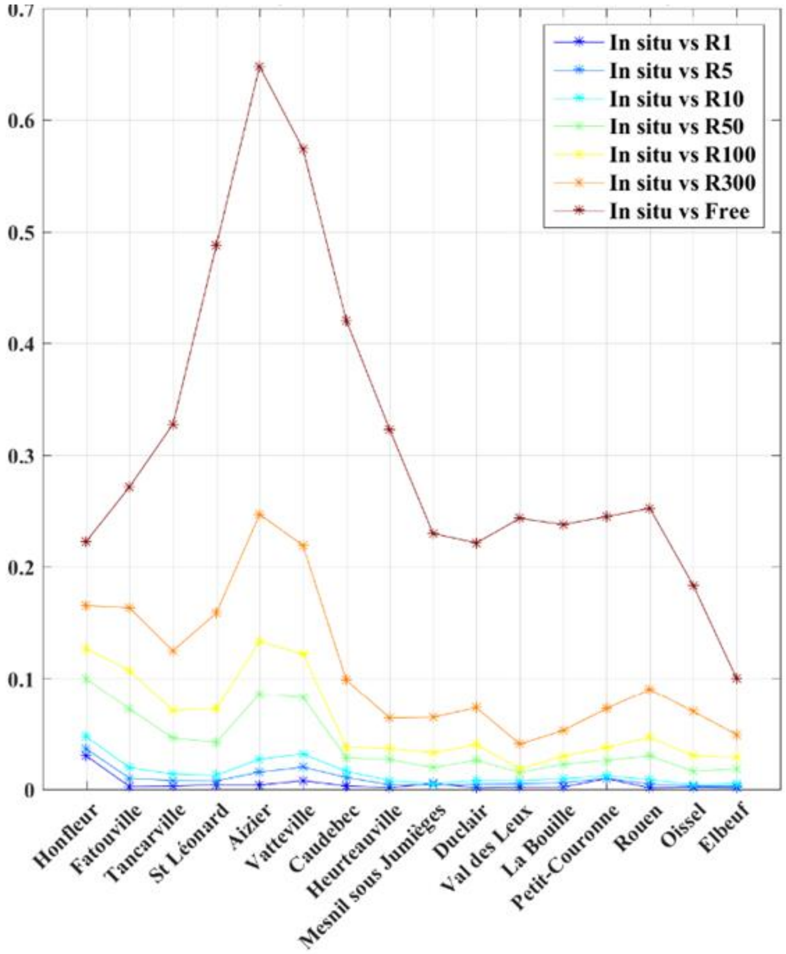


Figure 131: RMSDs in meters from in-situ tide gauge data and model outputs. The different tests were performed using the model with the optimal configuration parameters and constrained at all tide gauge stations by using different relaxation time scales. The caption shows the references of the relaxation time scales used in these experiences (ranging from 1 to 300 (r1 to r300)).

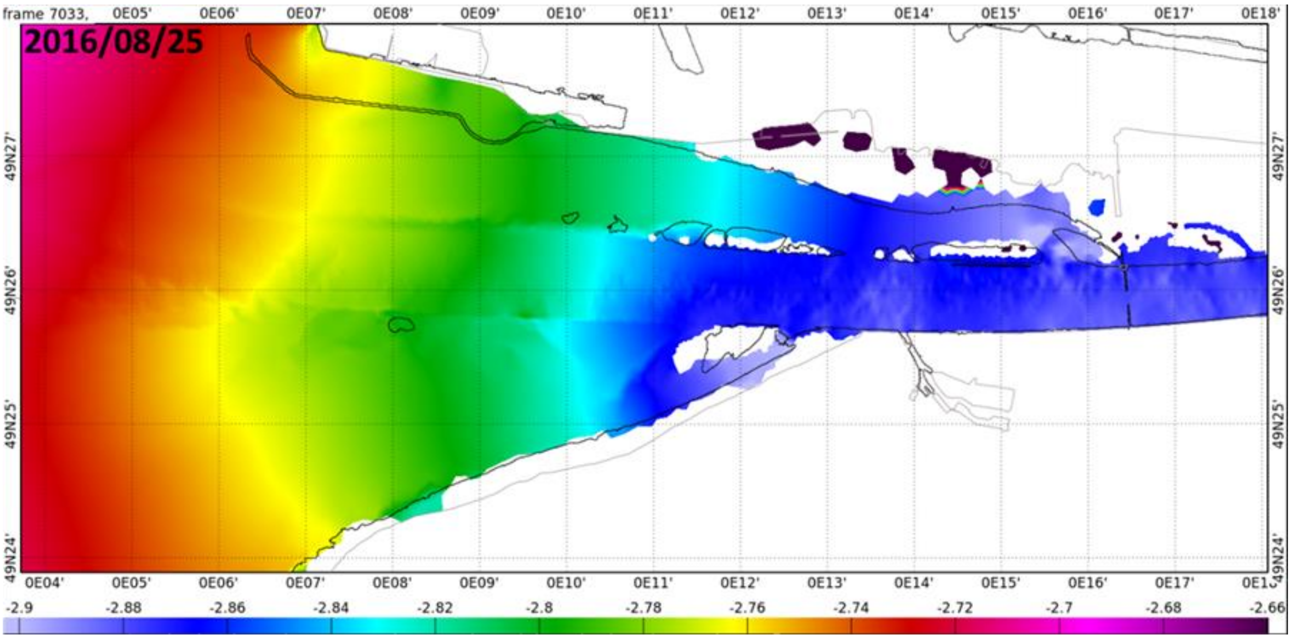


Figure 132: NDWI estimated from Sentinel-2 satellite image represented with a black line superimposed to the model output water surface elevation field in meters for 2016/08/25.

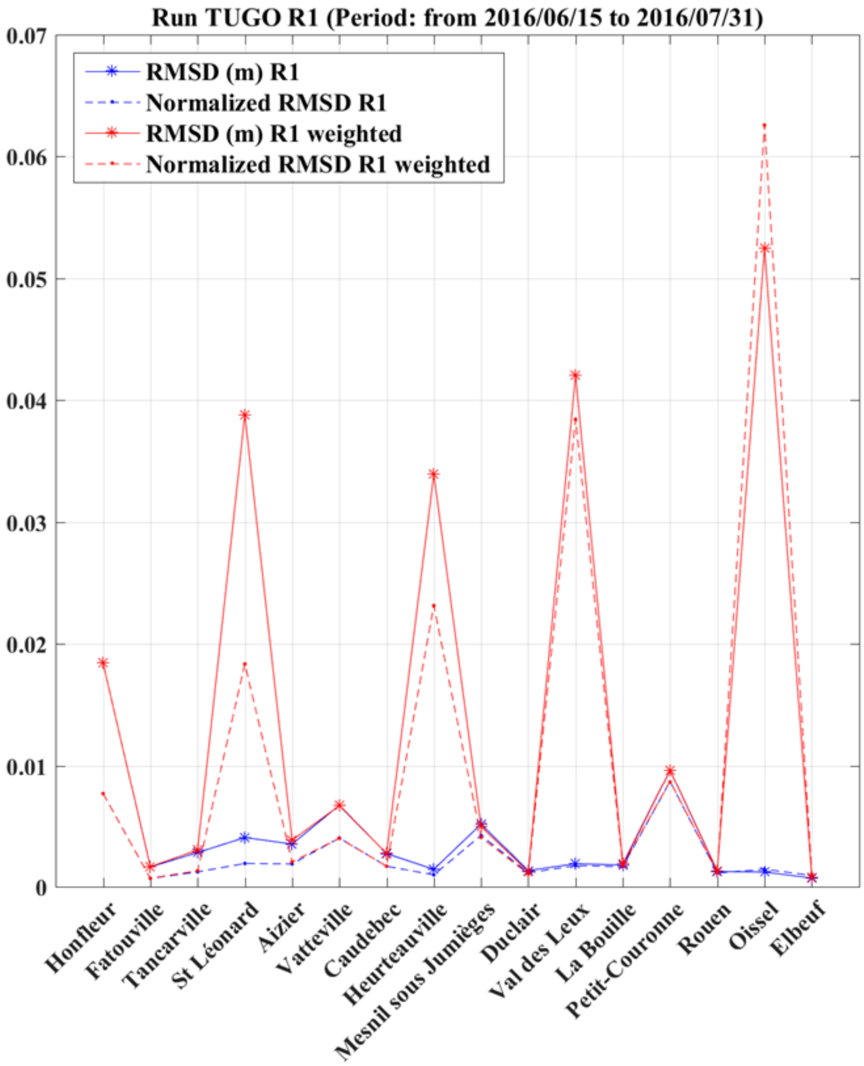


Figure 133: MSDs (filled lines) and normalized RMSDs (dotted lines) from in-situ tide gauge data and model outputs performed using the model with the optimal configuration parameters, relaxation time scales of 1 (r1) and the best assimilation scheme are shown in blue. In red, analogous to what is highlighted in blue, but with "St. Léonard", "Heurteauville", "Val des Leux and Oissel" stations relaxed.

9.3 Computing FRM on the Seine River in Honfleur

9.3.1 Computing the FRM

Following the results of the comparison between the tide gauges data and the different model output tests detailed in section 9.2, the complexity of the interactions between river flow and ocean dynamics in the Seine Estuary requires to locally constrain the model with tidal observations in order to obtain errors that are small enough to be useful for the altimetry Cal/Val activities for missions like SWOT and Sentinel-3. Moreover, to produce hydrodynamic simulations, the gauge time series used as upstream boundary condition needs to be as clean and complete as possible (no noise and no interruptions of measurements), which is difficult to ensure when the instrument is maintained by an external institute that is not necessarily aware of such operational use of the data. The existing gauge networks are often based on instruments of different types, different generations, and different levels of accuracy, which must be considered in the comparison with the model or in the data assimilation process. The processing of the tide gauges database requires considerable effort and time.

9.3.2 Comparison with Sentinel-3

The direct comparison between Sentinel 3 data with the model outputs will be realized in the near future.

9.3.3 Conclusion on this site

On this super-site we performed the campaigns to install the Micro-station under a Sentinel-3A track. Moreover, transects have been performed near the Micro-station and also upstream and downstream. Finally, we successfully developed and validated a regional model configuration aimed at stimulating the interactions between the ocean dynamics and the river flow in the Seine estuary, namely, to provide accurate simulations for Cal/Val Sentinel 3 and SWOT activities in the region. The in-situ measurements and model simulations showed very encouraging results. The comparison between observations obtained during the campaign and Sentinel 3 data with the model outputs could be some future important endeavours for the Cal/Val of satellite altimetry measurements of water surface height in the region. The analyses of the intercomparison in the Seine will bring new insight and will help further define such Cal/Val sites in the future.

10 The Issykkul Lake

10.1 Campaign performed on the site

10.1.1 In-situ sensors

The lake Issykkul is located in Kirghizstan. In the framework of different spatial missions this lake is a main place to study the performances of altimetry on lakes. This super-site has been used for a long time and there is a long continuity in the in-situ measurements on this lake. Several Sentinel-3A, Sentinel-3B and Sentinel-6 tracks cross the Lake. During the St3TART project, activities have been performed on the lake. The sensors have been installed under Sentinel-3A and Sentinel-3B ground tracks but also close to Sentinel-6 ground tracks. The in-situ sensors installed on the Issykkul lake are not connected and their data must be collected during field missions.

<u>October 2021:</u>

During this campaign the team collected the in-situ data from radar limnigraph on the East coast of the lake, GNSS and weather stations data.

<u>October 2022:</u>

In 2022 the main purpose of the campaign was to install a new in-situ site with a permanent GNSS, a permanent weather station and a radar limnigraph. This sensor was installed on the West coast to complete the one on the East coast and to measure at high temporal frequency the water level of the lake (therefore deduced dynamical effect like seiche), to correct for wet and dry troposphere, and to serve as reference point for further GNSS campaign using Double Difference processing together with PPP processing. As in 2021, during the mission the team has also collected up to date in-situ data from existing ground instrumentation (water level at 2 points, GNSS data from 2 sites, and weather data on the East coast).

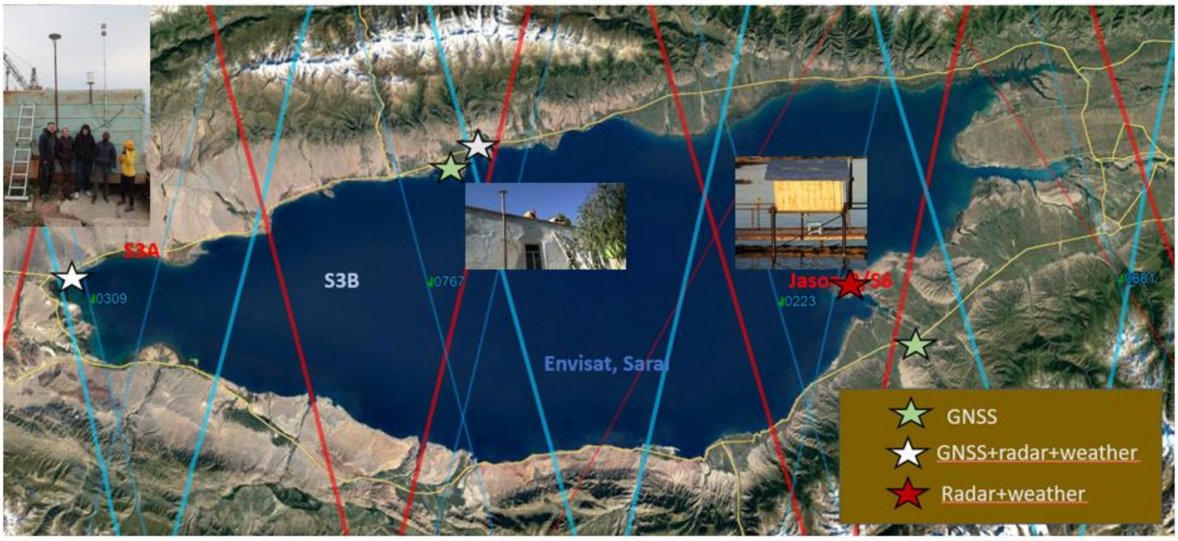


Figure 134: Current situation of the in-situ network for further Cal/Val activities on nadir altimeter and SWOT. 2 radars for high frequency (5 min) water level measurements and weather stations on West and East extremities of the lakes. 3 permanent GNSS receivers

The network of in-situ sensors on the Issykkul Lake is dense and well maintained by different entities. It is very important to include this study site into Cal/Val activities on Sentinel-3 to benefit from the knowledge acquired on this Lake.

10.1.2 Moving sensors

On the Issykkul lake 2 moving sensor campaigns have been performed. The aim of these campaigns is to measure the water level along the Sentinel-3 ground tracks. During those campaigns 2 types of moving sensors are used: "CalNaGeo" and "Cyclopée". Those sensors are described in the Technical Handbook [RD7].

October 2021:

During the campaign GNSS profiles along a Sentinel-3B ground track have been performed to validate the satellite measurements. tracks on the lakes for validation of S3B and in order to continue the mean lake surface calculation.

October 2022: GNSS profile along the Sentinel-3A and sentinel-6 for absolute bias calculation and validation of water height extraction from these satellites. Complete the mean lake surface for final estimation that will be used for SWOT Cal/Val and deployed for the first time the CalNaGeo instrument together with classical GNSS coupled with radar at the bow of the boat.

10.2 Computing FRM on the Issykkul Lake

10.2.1 Computing the FRM

Following the Cal/Val site classification detailed in part the TD-6 document (RoadMap) [RD6], this site corresponds to a complexity level 0 and a complexity level 1 site. Thanks to the installation of the instrumentation described in the previous paragraph we can compute the FRM measurement and then compare to Sentinel-3 data.

As mentioned before this site corresponds to a complexity level 0 and level 1 sites. The in-situ sensor is installed just under the satellite ground track on the lake shores. At this location the computation of the FRM is simple: it corresponds to the measurement of the in-situ sensor that has been configured to perform a measurement at the exact time of the Sentinel-3 pass. The Equation of the FRM on this case is:

$$\boldsymbol{WSH_{FRM}(t) \ = \ WSH_{IS}(t)}$$

In the middle of the lake the super site becomes a complexity level 1 site. We are not on a river so there is no slope to be accounted for. However other effect measured by moving sensors must be accounted for to compare the satellite measurements with in-situ data. On lakes the geoid influences the water height. When a moving sensor measurement is performed on the lake the height variation corresponds to the effect of the geoid and other physical effects as the influence of the wind. The mean of multiple measurements corresponds to the geoid correction that must be applied to the in-situ measurement. The Equation of the FRM in that case is:

$$\boldsymbol{WSH_{FRM}(t) \ = \ WSH_{IS}(t) + \Delta WSH_{MS}}$$

We can also perform complexity level 0 comparison on the middle of the lake under a Sentinel-3 ground track if a moving sensor campaign is planned at the same time as a Sentinel-3 pass.

10.2.2 Comparison with Sentinel-3

The following graphs correspond to the results of the measurement campaign of October 2022. Profiles measurements have been performed at the same time as Sentinel-3B. There is a high agreement between Sentinel-3B measurement and the moving sensor data. More results will be presented in a scientific paper (Crétaux et al.).

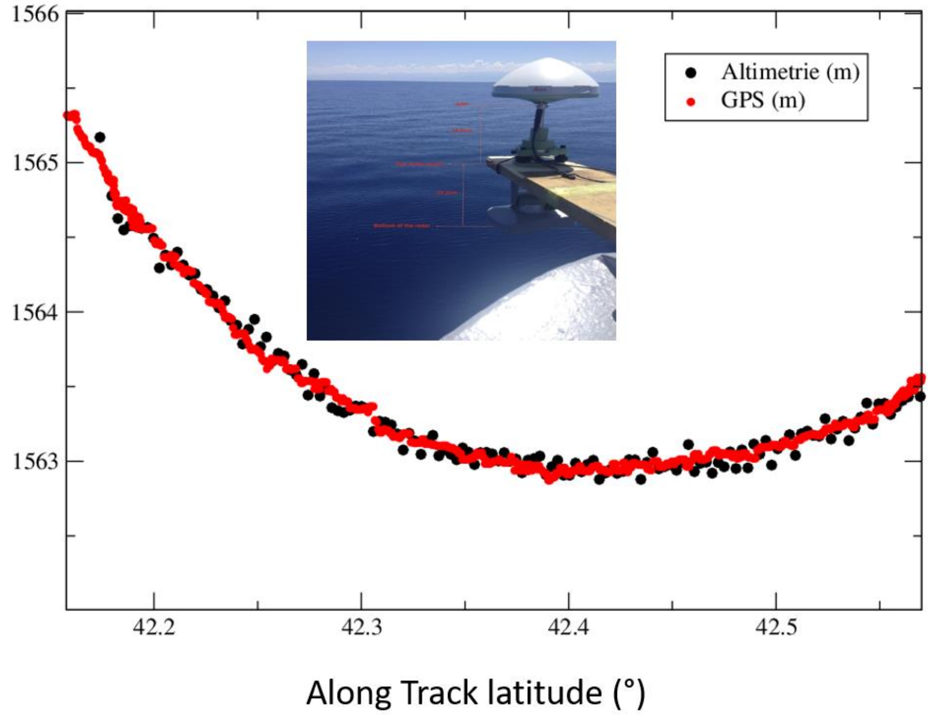


Figure 135: Comparison between GNSS vertical height along the Sentinel-3B track (10) during the cycle 58 (Oct 8 of 2021) at the time of the satellite pass. Standard deviation better than 2 cm. Bias < 2cm.

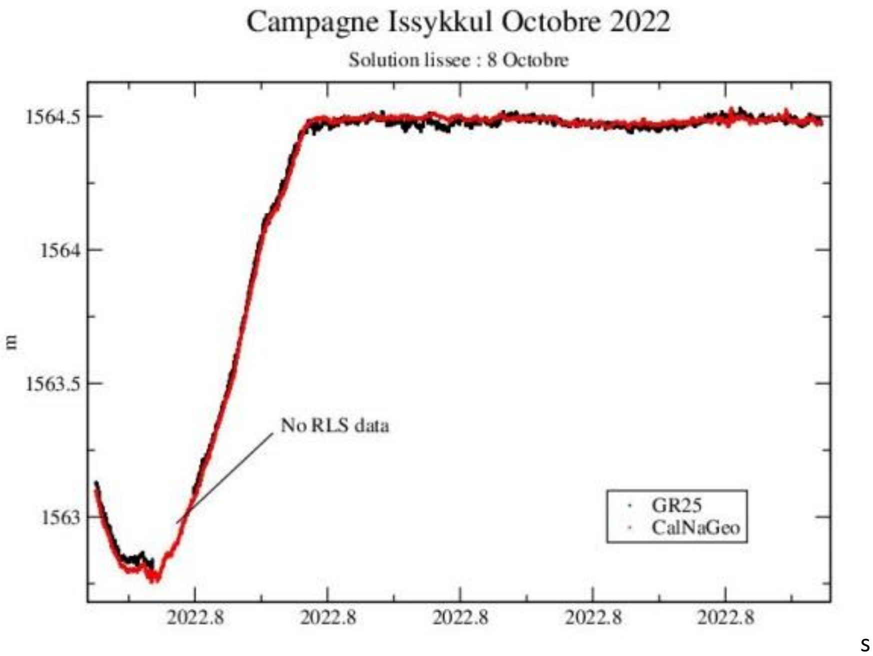


Figure 136: Zoom of the comparison shown in fig. 5 during the pass of Sentinel-3A on 8 of October. Sentinel data not yet processed for this pass (to be done soon)

10.2.3 Conclusions on this site

The Issykkul Lake is a well-known site providing very good FRM and comparison results for many years. It is important to maintain this site for long-term purposes. A dedicated paper will be released later in 2023 detailing the results of the 2022 campaign.

11 Opportunity sites

11.1 Computing the FRM

Following the Cal/Val site classification detailed in the TD-6 document (RoadMap) [RD6], the opportunity sites correspond to complexity level 0 site. The opportunity sites differ slightly from the complexity level 0 "super-sites". On opportunity sites we do not control the sensor, so we do not control the exact date of measurements. The FRM is obtained by interpolation. Following the recommendations related to this site class, we can compute the FRM measurement and then compare to Sentinel-3 data.

As mentioned before this site corresponds to complexity level 0 site. The in-situ sensor is installed just under the satellite ground tracks. The computation of the FRM is very simple: there is no slope to be accounted for, no other in-situ data required. The FRM simply correspond to the interpolation of the measurement of the in-situ sensor at the exact time of the Sentinel-3A pass for the ground track. The Equation of the FRM on these sites is:

$$\boldsymbol{WSH_{FRM}(t) = WSH_{IS}(t_{IS})}$$

11.2 Comparison with Sentinel-3

11.2.1 Example on some opportunity sites

11.2.1.1 Opportunity sites in the German network

For the German network and a few locations in the Netherlands and Switzerland, GIS gathered in-situ data from local gauges operated by national authorities. The acquisition of such measurements is rather difficult in Germany and mostly requires individual requests. Nonetheless, a decent amount of data was obtained and can be used for comparison with the water levels derived from Sentinel-3A/B measurements. Following the concept of opportunity sites, the validation of Sentinel-3A/B measurements by means of FRMs should be possible without any further corrections such as slope. In the German and Dutch networks, the opportunity sites are chosen as such that slope corrections are not necessarily due to either the small distance between local gauge and altimetric measurement location or the significantly flat topography. However, for the sites Mannheim, Oestrich-Winkel and Spay so-called water level profiles were used anyway due to the rare possibility to determine very precise slope estimates. These are based on orthometric height measurements of the Rhine's surface whereby boats navigating several reaches of the river performed observations in 100 m sampling distances. To be clear, these three opportunity sites can certainly be used without the corrections of slopes in the future. Slopes were simply used here because it is worth taking advantage of such a rare dense network and the fact that they provide a very precise first analysis opportunity.

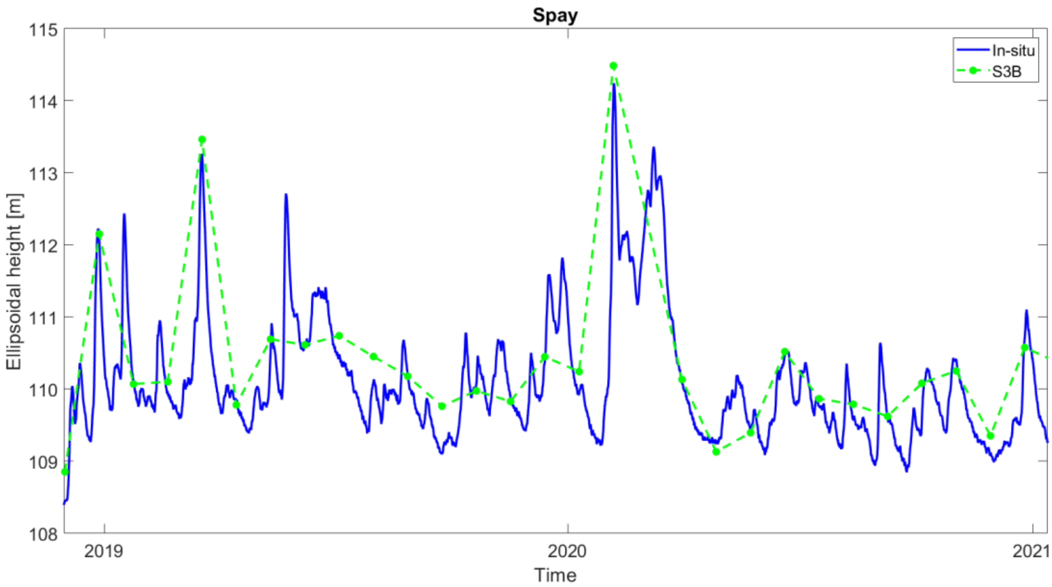


Figure 137 : A comparison between water levels from a local gauge and S3B measurements at Spay

Figure 137 represents one of many comparisons between water levels obtained from in-situ and altimetric measurements in the German network. This is the Spay virtual station located in a hilly region of Rhineland-Palatinate where slope corrections are crucial for large distances. In this case however, the local gauge in Braubach lies relatively close to the virtual station. From visual inspection, Figure 137 demonstrates an overall agreement between the two time-series indicating that the measurements of Sentinel-3B captured quite successfully the true water levels at the Spay virtual station.

11.2.1.2 Lauterbourg (Rhine)

As mentioned in the TD-6 [RD6] the opportunity sites are considered as level 0 sites; The satellite ground track should overfly the in-situ sensor and the slope should not be accounted for. In “Lauterbourg” we tried on this site to take into account the Slope to get an estimate of the error. We processed “Lauterbourg” site as a complexity level 1 super site with a slope estimation performed from IceSat-2 data. This site features a station in the Schapi network, making data access simple via the API. This site is close to a Sentinel-3 track (Relative Orbit 156). Water levels are provided in IGN69 with a daily time step.

We analyzed this station using the same approach as for the vorteX.io micro stations on the Rhine, namely by selecting the Sentinel-3 measurement that minimized the delta WSH with the station to ensure that the Sentinel-3 measurement was indeed targeting the correct location and not a neighboring water body.

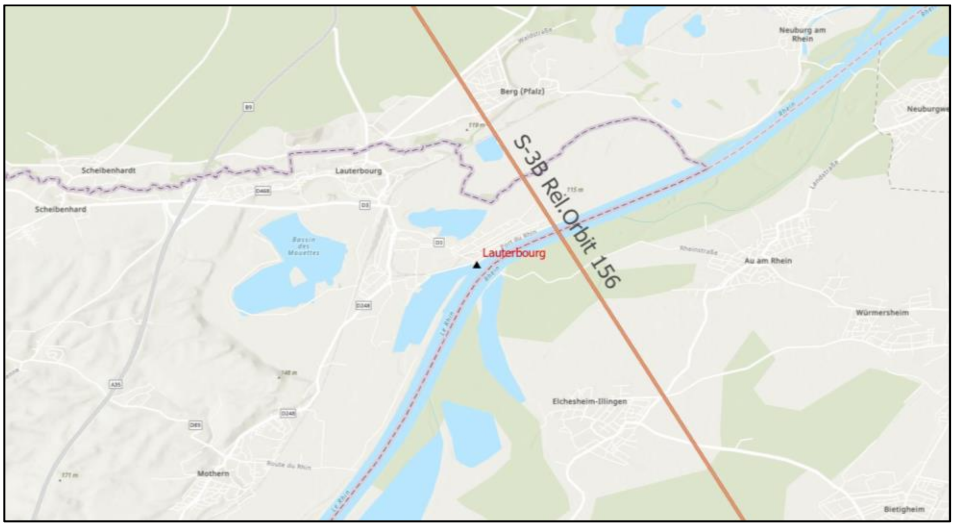
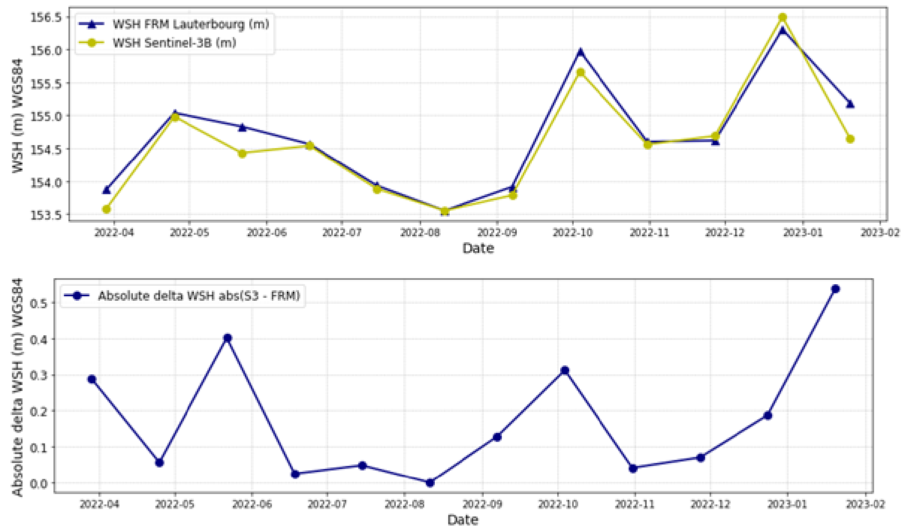


Figure 138: Map showing the location of the Lauterbourg station. It can be clearly seen that various water bodies are situated close to the station.




```
RMSE: 0.24
Average difference: 0.17 m
Median difference: 0.1 m
Maximum difference: 0.54 m
Minimum difference: 0.0 m
```

Figure 139 : Comparison between the FRM measurement (VigiCrue Station) and the Sentinel-3 measurement on Lauterbourg site. We obtain excellent results on this opportunistic site, with an absolute average difference of 0.17m

In all cycles, we obtain at least one unbiased measurement, and the difference in WSH between Sentinel-3 and the Lauterbourg station is very small across all dates. With an **RMSE of 0.24 m**, this site represents an excellent opportunity site in the field of hydrology for scientific reports. However, taking into account the slope increases the complexity of the processing and does not allow us to perform comparisons with Sentinel-3 data with a high number of opportunity sites as Lauterbourg.

11.2.2 Statistical analysis

11.2.2.1 French Network

The French Schapi network contains more than 3500 in-situ Vigicrues stations scattered over metropolitan France rivers (and some more in French Guyana and Reunion Island). Among them 1479 are referenced on IGN 1969 geoid in metropolitan France, over which we can convert the water surface elevation to reference it on the WGS84 ellipsoid and perform an absolute comparison with the altimetric data. The IGN1969 reference in-situ stations within less than 1km of the S3A and S3B theoretical ground track and for which the S3A & B Open Loop Tracking Command is fine-tuned were selected. With this constraint 45 stations were selected for the analysis (Figure 140).

As the river slope is unknown on these opportunity sites, only the S3A&B measurements falling within 150 m of the in-situ station position were selected to mitigate possible differences induced by river slope.

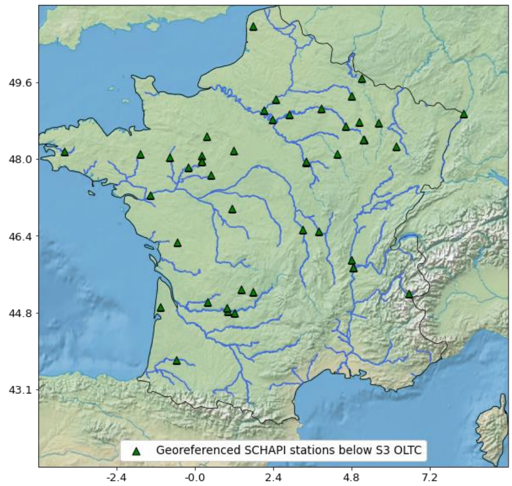


Figure 140: Map of the 45 Vigicrues stations (with an IGN 1969 georeferencing) directly located below S3A/B tracks with well-defined OLTCs.

The first diagnosis consisted in comparing the S3 L2 land PDGS WSH (obtained with OCOG retracker) to the in-situ measurements, the altimetry data selected are those since the missions start until 2023 March 25th with the above presented selection. The colocation time constraint to analyse an altimetric-in-situ data couple was set at 1 hour. Outliers further than 1 m were discarded as they represent errors in the retracking associated to nearby water bodies energy peak. 170 altimetric data points were selected and the distribution of their differences with respect to in-situ is represented on Figure 141. The **median difference is 13.7 cm** (blue line), and the **RMSE is of 27.9 cm**. This median difference represents the possible bias of the OCOG retracker plus the positive bias induced by Point Of Closest Approach (POCA) displacement due to possible river slope – the 150 m spatial selection constraint avoid being affected by measures of different elevations due to river slope but does not prevent POCA displacement effect. RMSE also includes the retracking noise contribution and is the quadratic sum of these biases and noise contributions with the WSH uncertainty (dominated by retracking noise). This **noise contribution** is therefore estimated to **24.3 cm**, fully consistent with the Lauterbourg analysis (at which the river is flat and hence no POCA displacement occurs).

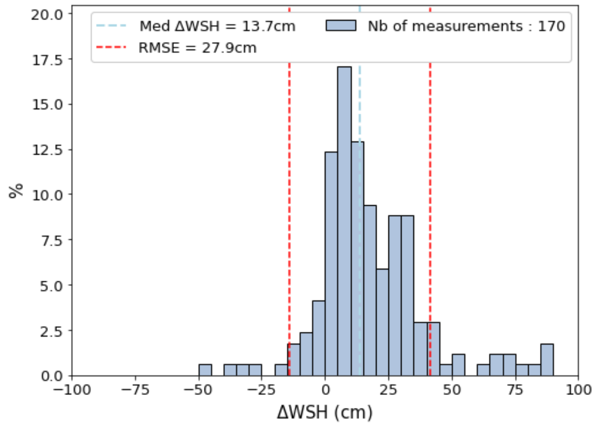


Figure 141: Histogram of the difference of WSH (ΔWSH) between S3 PDGS measurements (located at a distance shorter than 150m to the in-situ stations) and in-situ measurements.

Similar work was performed on the Pilot dataset of the S3A L2 Thematic Hydro products (which covers July 2022 to early March 2023 (namely cycles 87 to 95). The slight difference is that additionally the Topage (https://bdtopage.eaufrance.fr/) water mask was used to ensure these altimetric data are selected at the nadir of the water bodies probed by the in-situ gauges and in-situ gauges where the OLTC is suited (but not fine-tuned) were used, which allows increasing the number of in-situ stations used, as the time period covered by the Pilot dataset is limited. This does not have any impact as a suited OLTC (even if not fine-tuned) ensures the peak of backscattered energy falls within the altimeter receiving window. 22 altimetric data points were selected and the distribution of their differences with respect to in-situ is represented on Figure 142. The **median difference is 13.3 cm** (blue line), and the **RMSE is of 15.4 cm**. This median difference represents the possible bias of the OCOG retracker plus the positive bias induced by Point Of Closest Approach (POCA) displacement due to possible river slope. It is in full agreement with that estimated over the PDGS dataset, that is not expected to change, as the retracking used is the same - hence its possible bias -, and the effects of POCA displacement over the number of cases should average in between the two studies. The **noise contribution** is therefore estimated to **7.8 cm**, emphasizing the performance improvement on retracking noise estimated brought by the Thematic Hydro products.

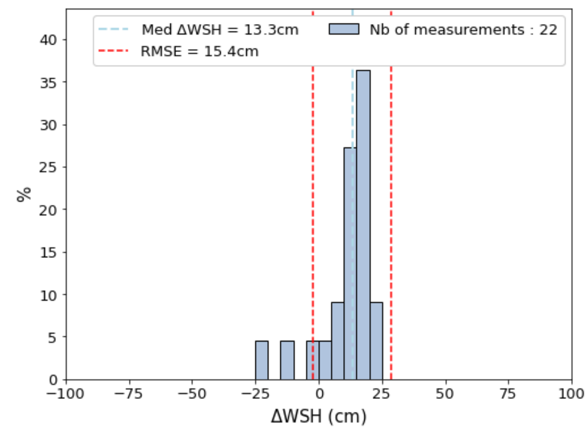


Figure 142: Histogram of the difference of WSH (ΔWSH) between S3 T-IPF measurements (located at a distance shorter than 150m to the in-situ stations) and in-situ measurements.

11.2.2.2 German network

As previously mentioned, this section focuses on comparing the water level time-series of the altimetry-derived and locally gauged measurements by computing the following two metrics: Correlation Coefficient (CC) and Root Mean Square Error (RMSE). Table 143 provides an overview of the three computed metrics across the German, Dutch and Swiss opportunity sites.

	Satellite	CC	RMSE [m]
Lake Constance	S3A	0.77	0.35
Lake Constance	S3B	0.96	0.33
Lake IJssel	S3A	0.90	0.05
Lake IJssel	S3B	0.81	0.13
Lake Zurich	S3A	0.29	0.58
Lake Zurich	S3B	0.25	0.52
Groote Lindt	S3A	0.33	1.06
Groote Lindt	S3B	0.16	1.90
Mannheim	S3A	0.97	0.30
Oestrich-Winkel	S3A	0.94	0.29
Sankt Sebastian	S3B	0.76	1.77
Spay 1	S3B	0.45	2.11
Spay 2	S3B	0.98	0.24
Vuren	S3A	0.86	0.39
Vuren	S3B	0.77	0.52

Table 143: A tabular overview of three computed metrics for all opportunity sites.

11.2.2.3 Swiss network

The Federal Office for the Environment (FOEN) provides hydrological monitoring of rivers and lakes within the Swiss territory. In the context of the St3TART project, only in-situ stations monitoring lakes have been used. For a preliminary analysis of the Water Surface Height (WSH) accuracy derived from S3A/B measurements, all the lakes with S3A/B transects which are monitored by in-situ stations have been selected. These lakes and stations are shown in Figure 144.

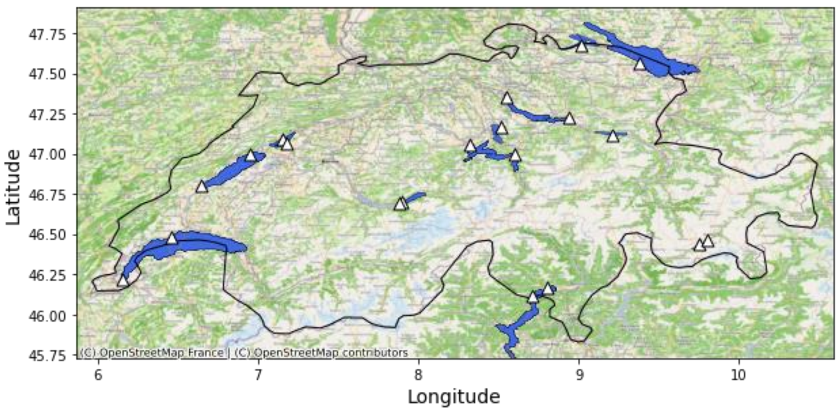


Figure 144: Map of the 14 Swiss lakes (blue areas) with S3A/B transects monitored by in-situ stations (white triangle)

Our analysis is applied to the three largest lakes, the Léman, Neuchâtel and Bodensee lakes. For each of them, there are two S3 transects, and for each cycle, we compute the median value of WSH per transect and the WSH from in-situ station at the same time (<1h). The in-situ and Sentinel-3 measurements are both converted on the local Swiss geoïd. The analysis of WSH accuracy over lakes requires to have measurements georeferenced on such local geoïd because unlike the analysis over rivers, the distance between the in-situ station and the Sentinel-3 measurements could be larger than the wavelength of the geoïd variation. This aim of this conversion is then to minimize the impact of the geoïd variation along the transect, which could bias the comparison of the two timeseries. The three pairs of Figures below show the map and the timeseries for each lake.

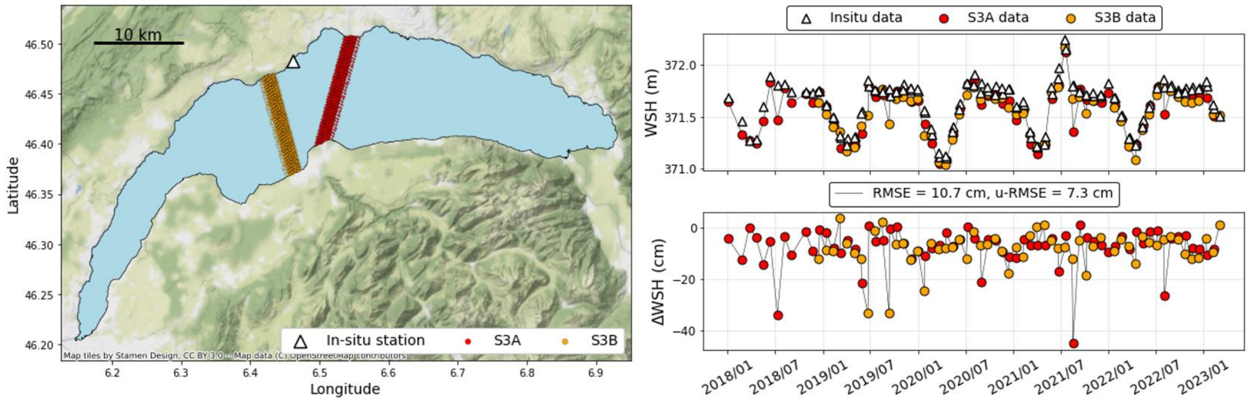


Figure 145: Map and time series on the Léman lake with S3A/B measurements (red/orange dots) and in-situ station (white triangle). Top time series: Median value of WSH for each S3A/B transects (red/orange dots) and in-situ value of WSH at the same time (<1h) (white triangle). Bottom time series: ΔWSH between S3A/B and in-situ measurements

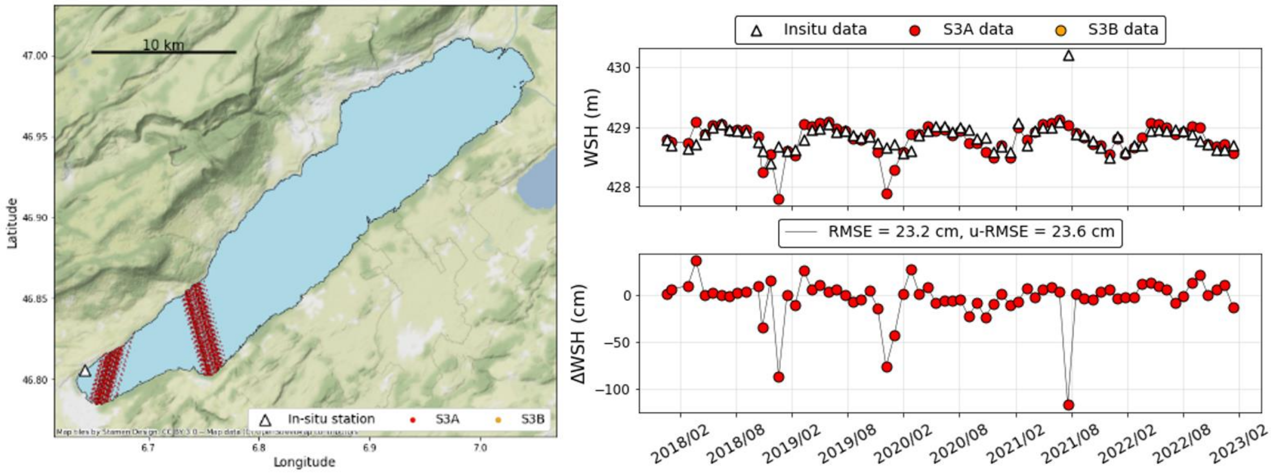


Figure 146: Map and time series on the Neuchatel lake with S3A measurements (red dots) and in-situ station (white triangle). Top time series: Median value of WSH for each S3A transects (red dots) and in-situ value of WSH at the same time (<1h) (white triangle). Bottom time series: ΔWSH between S3A and in-situ measurements

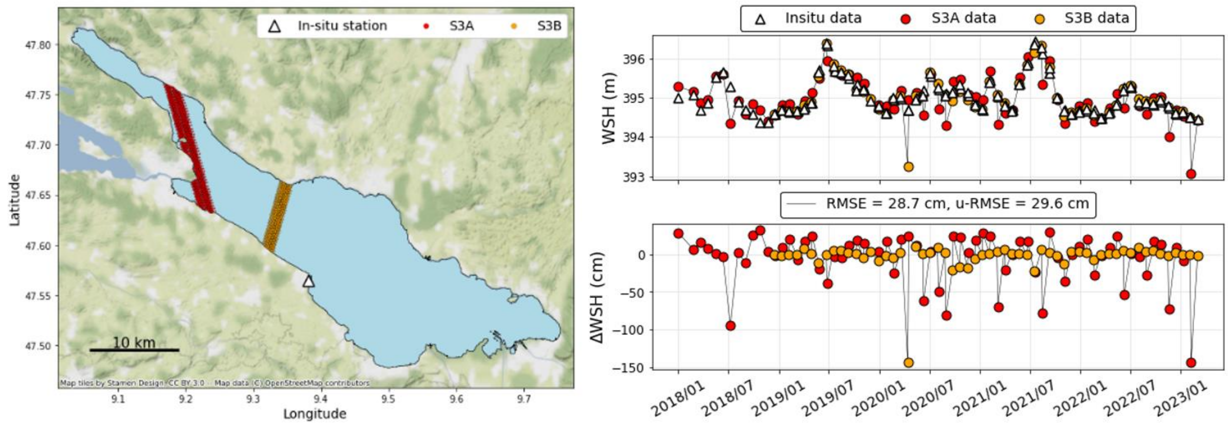


Figure 147: Map and time series on the Bodensee lake with S3A/B measurements (red/orange dots) and in-situ station (white triangle). Top time series: Median value of WSH for each S3A/B transects (red/orange dots) and in-situ value of WSH at the same time (<1h) (white triangle). Bottom time series: ΔWSH between S3A/B and in-situ measurements

The values of RMSE of the two timeseries for the three lakes are different, and its origin will require deeper investigations. However, in the favourable case of the Léman lake, where the in-situ station is located in-between and close to the two transects, the **RMSE value is around 10 cm** even if no editing has been applied before the computation of the median value of WSH for each cycle. For the Neuchâtel and Bodensee lakes**, RMSE values are higher than 20 cm**, and could be explained by a less favourable context, i.e., with the in-situ station located further from a transect to the other one.

11.2.2.4 US and Canadian lakes

In this analysis we investigate if existing gauges from the US geological survey (USGS) (https://waterdata.usgs.gov/nwis/sw/) and the Canadian Water office (https://wateroffice.ec.gc.ca/), can be used in a FRM validation approach to evaluate the quality of satellite-based water levels. Gauge data from the USGS is typically referenced to the National Geodetic Vertical Datum (NGVD) of 1929, the North American Vertical Datum (NAVD) of 1988, or w.r.t. a local reference. According to the USGS, the Gauge uncertainty of the water level is approximate 1.2 cm when approved. For a comparison of the gauge- and satellite-based water levels a common reference in absolute space must be applied. The Uncertainty related to the transformation of the US vertical reference surfaces to the satellite-based reference surfaces WGS84/EGM2008 is according to NOAA (https://vdatum.noaa.gov/vdatumweb/) 0.065/0.165 m, respectively. The Canadian gauges are typically referenced in a local system or Canadian Geodetic Datum of 1928 – CGVD28. To avoid errors related to datum transformation we will here focus on evaluating the satellites' ability to capture the relative variations of the water levels, though it is not in agreement with the FRM protocol. In order to advice a future validation strategy using existing gauges we investigate the quality influence of lake ice, distance to gauge, OLTC updates, potential errors in the lake shoreline boundaries. Figure 148 shows the locations of the US and Canadian gauges used in the analysis.

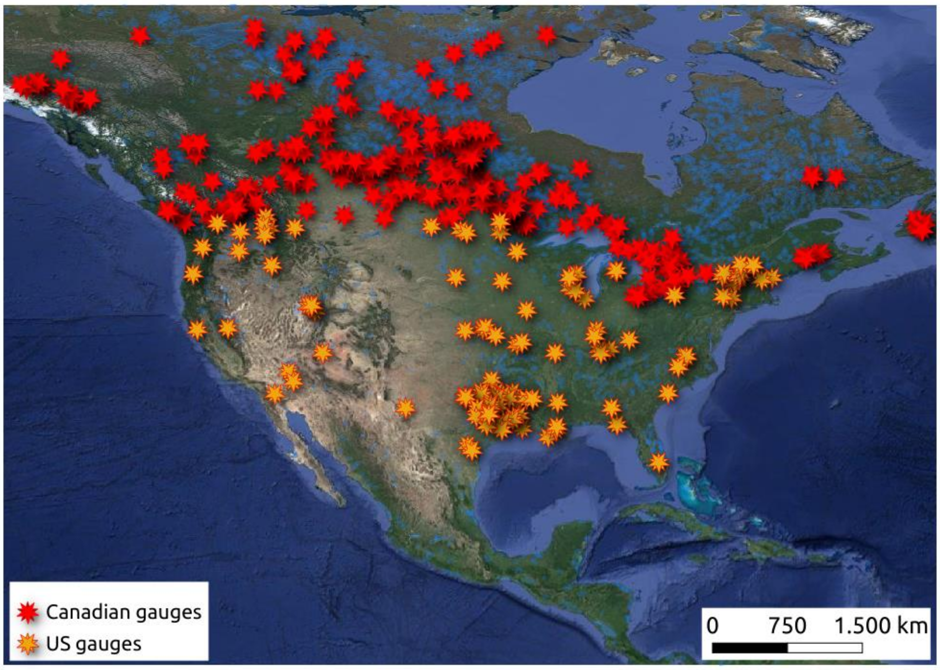


Figure 148: Location of the included gauges

In the following we provide the validation results based on the OCOG retracker. To extract the S3A and S3B measurements over lakes we use a subset of the SWOT Prior Lake database ([RD23],[RD24]), defined as lakes with an area above 20 km^2. This amounts to more than 7 000 lakes visited by S3A and S3B. Additionally, we filter the measurements based on the occurrence value from the Global Surface Water Explore ([RD25]). For all altimetry measurements we retrieve the occurrence value and keep those where the occurrence value is 90% or higher, for further analysis. Once the data is extracted, we reconstruct water level time series per satellite, track using the "R" package "tsHydro" ([RD26]).

To evaluate S3A and S3B estimated water levels with respect the gauge data we calculate the following summary statistics; root mean square error, correlation, and percentage of valid observations. Here the percentage of valid observations is defined as the percentage of observations that is within 1 meter of gauge level (bias corrected) at the time of the satellite observation. In the evaluation we only include the summary statistics if the gauge and satellite water level is available for at least 12 common times.

When evaluating the ability of S3A and S3B to capture lake levels, we must differentiate between noisy and erroneous observations, as well as external errors that are unrelated to the altimetry data. Examples of external errors are, lake mask errors, a wrongly positioned range window, and geoid errors. Examples of erroneous altimetry observations that is not representing the nadir water surface can be related to off-nadir targets and the presence of lake ice. To account for this in the evaluation we have done the following investigations:

- Investigate the reason for large RMSE values to identify RMSE values that represent the actual quality of the S3A and S3B based water levels.
- For high latitude lakes, we perform the evaluation based on summer data only to identify the influence of lake ice in the statistics.
- To reduce geoid related errors, we reconstruct the water level time series per track
- Test is the distance between that gauge and altimetry track influences the validation report

For the US and Canadian lakes, we get 130 and 606, lake-track-gauge combinations. If more than one gauge is available for the lake, we use the one with the smallest gauge-track distance. Figure 152, Figure 149, and Figure 150 provide the results of the validation analysis. Based on all pairs we find an RMSE of 20 cm and 28 cm for the US and Canadian cases, respectively. As seen on Figure 148 many of the considered lakes are located at high latitudes and will be affected by lake ice (see Figure 151). We find a considerable decrease in the RMSE when the validation is based on summer data only.

During the lifetime of the satellites there has been severable OLTC updates to improve the positioning of the range window. Hence, the RMSE should therefore improve if only the most recent data is used in the validation. To test this, we discard data prior to August 2020 (S3B OLTC v.3) for the US pairs, which leads to a decrease in the RMSE of 4 cm. A similar analysis is done for the Canadian pairs, where data is discarded prior to March 2019 (S3A OLTC v5). This leads to a decrease in the RMSE of 7 cm. The March 2019 limit was selected to ensure more data for the validation as the Canadian gauge data (historical product) is not up-to-date. RMSE values larger than 1 m are mainly related to OLTC updates during the lifetime (see Figure 151) of the satellites and errors in the lake mask, causing the gauge level and satellite water level to be incomparable. Only in a few cases is a large RMSE value related to noisy water levels (see Figure 151). Additionally, we have tested if the RMSE increases as a function the distance between the gauge and the satellite measurements (see Figure 153). Based, on the Canadian pairs, we find an increase in the RMSE as the distance increases. This result should be reviewed critically, as there are fewer pairs with a large distance.

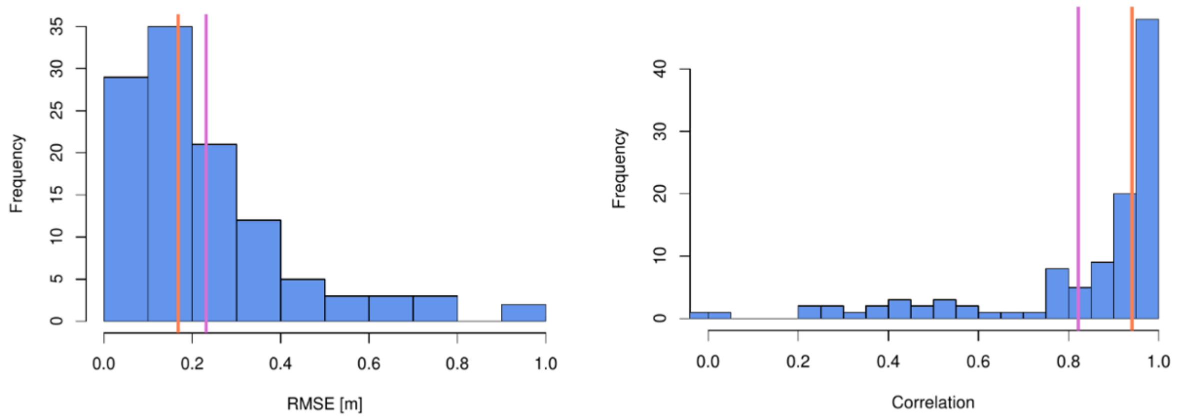


Figure 149: The distribution of RMSE and correlation for the US lakes. RMSE values larger than 1 are not presented here

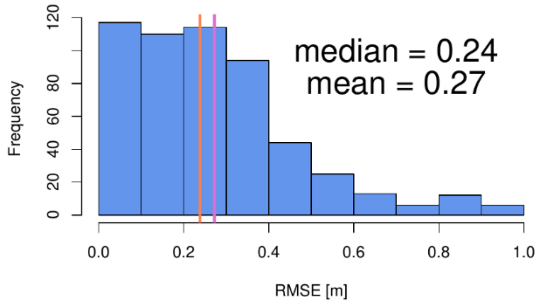


Figure 150:The distribution of RMSE for the Canadian lakes. RMSE values larger than 1 are not presented here

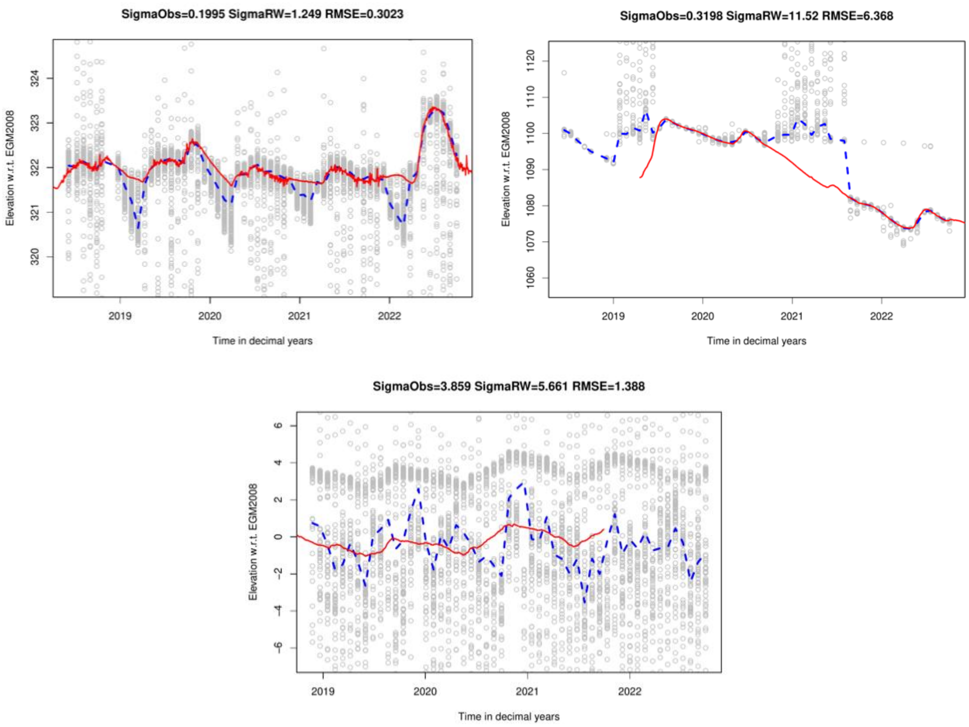


Figure 151: Lake level time series to illustrate reasons for large RMSE values. Top left: Lake of the woods, presence of lake ice. Top right: Lake Powel, a wrongly positioned range window. Bottom: Lake Okeechobee, noisy data.

Region	# Pairs	RMSE [m]	Correlation	# RMSE > 1
US	130	0.20	0.93	16
US Summer	123	0.11	0.96	15
US after 08-2020	121	0.16	0.93	11
CA	606	0.28	0.83	81
CA Summer	508	0.12	0.92	67
CA after 03-2019	513	0.21	0.90	33
CA close gauge	448	0.26	0 86	56

Figure 152: A statistical summary of the different analysis for the two regions. Here "# Pairs" represent the number of lake-track-gauge combinations used in the analysis. The reported value of the RMSE and correlation represent the median of all pairs. "# RMSE > 1" represents the number of RMSE values larger that 1 out of the total number of pairs.

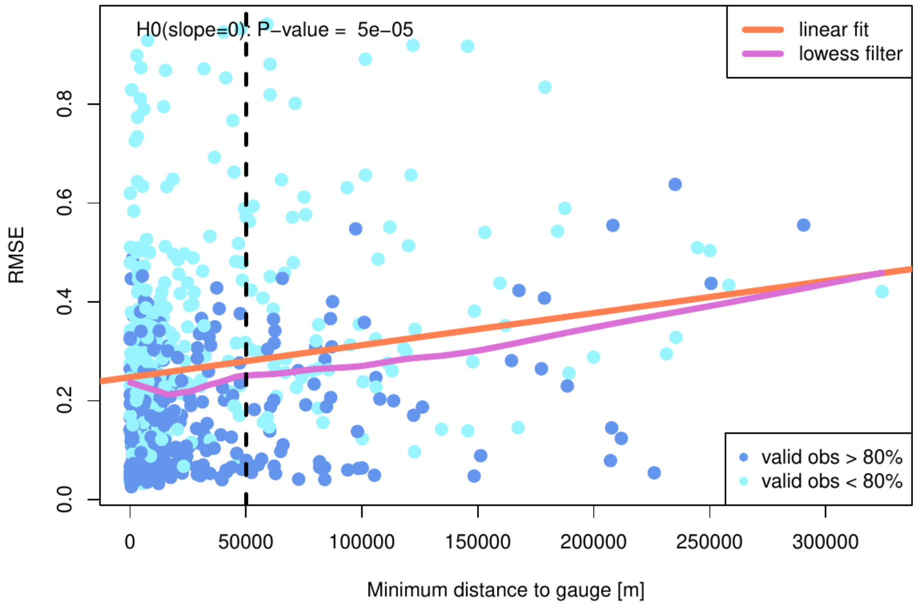


Figure 153: RMSE as a function of distance between the gauge and altimetry measurements based on the Canadian pairs.

Conclusion and recommendations based on the study: The gauges from the USGS and the Canadian water office provide precise water levels, though the absolute reference is inaccurate or not existing in the global reference of the satellites, over many lakes in different climatic environments. Despite this, they make an important contribution in the validation process of water level based on satellite altimetry. Based on our findings we recommend only to includes gauges less than 50 km from the altimetry data, as degradation of the validation results was found to be correlated with the distance. Additionally, lakes with a seasonal ice cover may be included, but only observations from ice free periods should be used to evaluate the quality at the satellite-based water levels.