St3TART
FRM for Sentinel-3 Land Altimetry

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

TD-6-1: Roadmap for S3 STM Land FRM operational provision for inland waters

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Acronyms

AD	Applicable Document
AIPo	Agenzia Interregionale del Fiume Po
AOI	Area Of Interest
ALS	Airborne Laser Scanner
ATM	Airborne Topographic Mapper
AUV	Autonomous Underwater Vehicle
BVLoS	Beyond Visible Line of Sight
CEN	Centre d'Etudes de la Neige
CGLS	Copernicus Global Land Service
CO	ESA Contract Officer
CS-2	CryoSat-2 mission
CSV	Comma-Separated Values
DEM	Digital Elevation Model
DMS	Digital Mapping System
EEA	European Environment Agency
EM	Airborne Electromagnetic Induction
EOB	End Of Business
ESA	European Space Agency
EU	European Union
FB	Sea Ice Freeboard
FFP	Firm Fixed Price
FFSAR	Fully Focused SAR
FIR	Flight Information Regions
FM-CW	Frequency-modulated continuous-wave radar
FOEN	Federal Office for the Environment
FR	Final Review
FRM	Fiducial Reference Measurement
GCP	Ground Control Points
GEM	Ground based ElectroMagnetic
GNSS	Global Navigation Satellite System
GPR	Ground Penetrating Radar
GPS	Global Positioning System
GRDC	Global Runoff Data Centre

GRP	Ground Reference Point
HDD	Hard Disk Drive
HR	High Resolution
IMB	Ice Mass Balance
INS	Inertial Navigation System
IOCR	In-Orbit Commissioning Review
ISPRA	Instituto Superiore per la Protezione e la Ricerca Ambientale
KO	Kick-Off
KOM	Kick-Off Meeting
L1	Level 1
L2	Level 2
LAM	Low Altitude Mode
LOCSS	Lake Observations by Citizen Scientists & Satellites (OECS in France)
LVIS	Land, Vegetation and Ice Sensor
LRM	Low Resolution Mode
MFF	Multi-annual Financial Framework
MoM	Minutes of Meeting
MPC	S3 Mission Performance Cluster
MSS	Mean Sea Surface
MVP	Minimum Viable Product
N/A	Not Applicable
NMI	National Metrology Institute
NWD	Normal Working Day
OC	Operational Challenges
OCOG	Offset Centre Of Gravity
OIB	Nasa Operation IceBridge
OLTC	Open Loop Tracking Commands table
OS	Operating System
OSSE	Observing System Simulation Experiments
PACF	Permanent Altimeter Calibration Facility
PDF	Portable Document Format
PM	Progress Meeting
PMP	Project Management Plan
POCA	Point Of Closest Approach
PPK	Post Processed Kinematic
PPP	Precise Point Positioning

PRF	Pulse Repetition Frequency
QWG	Quality Working Group
R&D	Research & Development
RD	Reference Document
RO	Routine Operational Phase
RTK	Real-Time Kinematic positioning
RULS	Range Under the Level of the Sonic gauge
S3	Copernicus Sentinel-3 mission
S3VT	Sentinel-3 Validation Team
S4B	Skype For Business
S6	Copernicus Sentinel-6 mission
SAMS	Scottish Association for Marine Sciences
SAR	Synthetic Aperture Radar
SCalSIT	Super CalVal Site Identifier Tool
SI	Système International
SILDAMS	Sea-Ice Lead Detection Algorithm using Minimal Signal
SIMBA	Snow and Ice Mass Balance Array
SLA	Sea Level Anomaly
SMP	SnowMicroPen
SRAL	Synthetic Aperture Radar Altimeter
SIRAL	CryoSat's SAR Interferometric Radar Altimeter (SIRAL)
SSH	Sea Surface Height
St3TART	Sentinel-3 Topography mission Assessment through Reference Techniques
STM	Surface Topography Mission
SWOT	Surface Water and Ocean Topography mission
TC	Technological Challenges
TD	Technical Deliverable
TO	ESA Technical Officer
UAV	Unmanned Aerial Vehicle
ULS	Upward Looking Sonar
UWB	Ultra-Wideband
VC	Video-Conference
WP	Work Package

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-050	TD-6: Roadmap for S3 STM inland water FRM operational provision
[RD6]	NOV-FE-0899-NT-042	TD-1 FRM Protocols and Procedure for S3 STM Inland Water Products
[RD7]	NOV-FE-0899-NT-053	TD-10-1: FRM Campaign Implementation Plan for S3 STM Inland Water products
[RD8]	Sandwell, David & Smith, Walter. (2014). Slope correction for ocean radar altimetry. Journal of Geodesy. 88. 10.1007/s00190-014-0720-1.	
[RD9]	Meybeck M., Pasco A. & Ragu A., 1996, Evaluation des flux polluants dans les eaux superficielles. Etude Interagence de l'eau – Ministère de l'Environnement, 3 tomes	
[RD10]	Sauquet E., Dupeyrat A., Hendrickx F., Labedade R., Samie R., Vidal, J-P., Perrin C., Boudhraa H., Gaëckler M. (2009) — Impacts anthropiques et étiages de la Garonne à l'horizon 2030. Actes du "Colloque 193 SHF : Etiages, Sécheresses, Canicules rares et leurs impacts sur les usages de l'eau", Lyon, France, 7-8/10/ 2009.	
[RD11]	Martin, E., S. Gascoin, Y. Grusson, C. Murgue, M. Bardeau, F. Anctil, S. Ferrant, R. Lardy, P. Le Moigne, D. Leenhardt, V. Rivalland, J.-M. Sánchez Pérez, S. Sauvage, and O. Therond. 2016. "On the use of hydrological models and satellite data to study the water budget of river basins affected by human activities: examples from the Garonne basin of France." Surveys in Geophysics 37(2): 223-247. doi:10.1007/s10712-016-9366-2.	
[RD12]	EOP-SM/2184/CD-cd	Sentinel-3 Mission Requirements Traceability Document (MRTD)
[RD13]	Michał Halicki, Tomasz Niedzielski, The accuracy of the Sentinel-3A altimetry over Polish rivers, Journal of Hydrology, Volume 606, 2022,127355, ISSN 0022-1694, https://doi.org/10.1016/j.jhydrol.2021.127355.	
[RD14]	Egido, Alejandro, et Walter H. F. Smith. « Fully Focused SAR Altimetry: Theory and Applications ». IEEE Transactions on Geoscience and Remote Sensing 55, no 1 (janvier 2017): 392-406. https://doi.org/10.1109/TGRS.2016.2607122.	
[RD15]	Ehlers, Frithjof, Florian Schlembach, Marcel Kleinherenbrink, et Cornelis Slobbe. « Validity Assessment of SAMOSA Retracking for Fully-Focused SAR Altimeter Waveforms ». Advances in Space Research, 23 novembre 2022. https://doi.org/10.1016/j.asr.2022.11.034.	

[RD16]	Messager, M.L., Lehner, B., Grill, G., Nedeva, I., Schmitt, O. (2016). Estimating the volume and age of water stored in global lakes using a geo-statistical approach. Nature Communications, 7: 13603. https://doi.org/10.1038/ncomms13603	
[RD17]	Jean-Francois Pekel, Andrew Cottam, Noel Gorelick, Alan S. Belward, High-resolution mapping of global surface water and its long-term changes. Nature 540, 418-422 (2016). (doi:10.1038/nature20584)	
[RD18]	Tarpanelli, A.; Barbetta, S.; Brocca, L.; Moramarco, T. River Discharge Estimation by Using Altimetry Data and Simplified Flood Routing Modeling. Remote Sens. 2013, 5, 4145-4162. https://doi.org/10.3390/rs5094145	
[RD19]	Tarpanelli A., Brocca L., Barbetta S., Faruolo M., Lacava T., Moramarco T. (2015) Coupling MODIS and radar altimetry data for discharge estimation in poorly gauged river basin. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 8(1), 141-148. http://dx.doi.org/10.1109/JSTARS.2014.2320582.	
[RD20]	Tarpanelli, Angelica & Camici, Stefania & Nielsen, Karina & Brocca, Luca & Moramarco, T. & Benveniste, Jérôme. (2019). Potentials and limitations of Sentinel-3 for river discharge assessment. Advances in Space Research. 68. 10.1016/j.asr.2019.08.005.	
[RD21]	Raphael Schneider, Angelica Tarpanelli, Karina Nielsen, Henrik Madsen, Peter Bauer-Gottwein, Evaluation of multi-mode CryoSat-2 altimetry data over the Po River against in situ data and a hydrodynamic model, Advances in Water Resources, Volume 112, 2018, Pages 17-26, ISSN 0309-1708, https://doi.org/10.1016/j.advwatres.2017.11.027.	
[RD22]	Alessio Domeneghetti, Angelica Tarpanelli, Luca Brocca, Silvia Barbetta, Tommaso Moramarco, Attilio Castellarin, Armando Brath, The use of remote sensing-derived water surface data for hydraulic model calibration, Remote Sensing of Environment, Volume 149, 2014, Pages 130-141, ISSN 0034-4257, https://doi.org/10.1016/j.rse.2014.04.007.	
[RD23]	Domeneghetti, Alessio & Molari, Giada & Tourian, Mohammad & Tarpanelli, Angelica & Behnia, Sajedeh & Moramarco, T. & Sneeuw, Nico & Brath, Armando. (2021). Testing the use of single- and multi-mission satellite altimetry for the calibration of hydraulic models. Advances in Water Resources. 151. 103887. 10.1016/j.advwatres.2021.103887.	
[RD24]	Nielsen, K.; Andersen, O.B.; Ranndal, H. Validation of Sentinel-3A Based Lake Level over US and Canada. Remote Sens. 2020, 12, 2835. https://doi.org/10.3390/rs12172835	
[RD25]	EEA/IDM/15/026/LOT1	Hydrological in situ data requirements and availability. Issue: 1.0, 05/12/2019
[RD26]	CCVS.CLS.D1.2	Altimetry Missions Cal-Val Requirements
[RD27]	CCVS.ACR.D3.6	Copernicus CalVal Solution
[RD28]	NOV-FE-0899-NT-101	FRM Campaign final report over inland waters
[RD29]	NOV-FE-0899-NT-110	TD-14 – St3TART Scientific Paper
[RD30]	EOP-SMO/1151/MD-md	Sentinel-3 Mission Requirements Document (MRD)

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1. Introduction

1.1. Purpose and scope

This document is the Roadmap for S3 STM Land FRM operational provision for the "Sentinel-3 Topography mission Assessment through Reference Techniques (St3TART)" project, [RD1].

As agreed with ESA, this document is specific to the inland water surface type. An executive summary report covering the three surface types considered in St3TART (Hydrology, Sea ice and Land ice) and identifying the synergies between them, is provided as a scientific paper (see [RD29] for more information).

This roadmap presents a set of Cal/Val super sites given as demo sites for installing a complete instrumentation to provide operational S3 STM FRM over inland waters. These sites correspond to different use cases and can serve as examples to be replicated wherever useful.

The objective of this approach is to federate the international community around the system of Opportunity and super Cal/Val sites to create an international programme over continental hydrology zones similar to the in-situ measurement system used for many years over the ocean. Indeed, the ocean in-situ system used for Cal/Val activities also relies on a similar approach, Cal/Val super sites such as Senetosa (CNES), Gavdos (ESA/EUM), Harvest (NASA) and Bass Strait (CSIRO) combined with an international program of in-situ measurements (represented by Opportunity sites in this roadmap) such as the Argo network.

1.2. Overview of this document

In addition to this Introduction chapter, this Roadmap for S3 STM Land FRM operational provision includes the following chapters:

- Strategy for Operational FRM provision over inland water
- Cal/Val super sites over rivers
- Cal/Val super sites over lakes
- Existing in-situ sensor networks for Opportunity Cal/Val sites
- Metrological uncertainty analysis for inland FRM

In the TD-1 document [RD6] it has been demonstrated that each virtual station site over inland water bodies has specific characteristics, especially concerning the impact of the natural excursion of the satellite track due to the current orbit control constraints, the local water topography and roughness and their temporal variation, which are different for each site. This is particularly true over rivers but is also applicable to lakes to some extent.

The roadmap proposed in this document aims at describing an implementation of a sustainable operational FRM provisioning over inland water with a specific focus on the FRM quality (meeting FRM requirements), the operational production of these reference measurements and the strong will to federate the Cal/Val community to create an emulation around the provision and use of these FRMs.

That is why this roadmap proposes Cal/Val "super sites" that are given in this project as demonstrators that can be duplicated on other sites, thanks to a recipe described in the following chapters. This recipe will cover the different aspects, from the sensor types to use to the strategy to produce FRM. An annual estimate of the running costs of each site will also be made and provided to give a baseline budget for any future open call dedicated to the deployment of new sites. Finally, we also propose to combine this super site approach with the use of existing in-situ networks to involve and federate local partners from different countries.

The strategy we propose in this document is intended to be generic, though with differences between rivers and lakes. However, this strategy is not directly applicable to high-latitude sites. Indeed, lakes and rivers located at high latitudes are of particular interest for Sentinel-3 Cal/Val activities, notably because of the tighter grid of ground tracks allowing for shorter revisit time, however the presence of ice requires specific means and analysis that were not analysed during this project framework. Thus, and in agreement with our proposal, this aspect is not further developed here.

2. Strategy for operational FRM provision over inland water

2.1. MPC requirements for operational Cal/Val activities

S3 LAND STM MPC performs routine as well as in-depth analysis of the quality of the altimetric data over inland waters. Routine activities consist in emitting a Cyclic Performance Report over Inland Waters within 5 days after the end of each cycle. This cyclic report contains absolute comparisons to in-situ data even for STC products. This sets the following requirements on the FRM:

- FRM shall have a **reliable timeliness < 1-2 days** for **STC products**. For **NTC products**, consolidated FRM shall have a **timeliness of 2 weeks**.
- FRM **shall be georeferenced** to be useful for absolute comparison of water surface heights
- FRM shall consist of **long timeseries** to be able to detect anomalies in the evolution of the in-situ/altimetry data comparison metric (namely RMSE), at least one year to cover a hydrological cycle.

The in-depth analysis performed by MPC covers both rivers and lakes surfaces. Among these activities, the validation of the Full Mission Reprocessing requires having a long in-situ time series covering the life of the mission. In-situ datasets since S3A launch early 2016 are useful to validate the reprocessing campaigns and assess the compliance to the "**consistent, long-term** collection of remotely sensed data, of **uniform quality**" requirement present in S3 MRD [RD30]. MPC therefore supports the policy of 'making existing means to FRM standards.

MPC is also aiming at building the WSH error budget over inland waters on the reconstructed WSH. As presented in TD-1 [RD6], uncertainty breakdown in between the different contributors, the main contributor to the error budget is the range uncertainty. It has been shown within S3 LAND STM MPC studies that the accuracy of the L2 Thematic Hydrology products can be as good as 5 cm RMSE over flat canals (see Figure 1). Consequently, FRM are needed with better than 5cm accuracy over such favourable cases to quantify the retracking algorithm error budget (bias and noise).

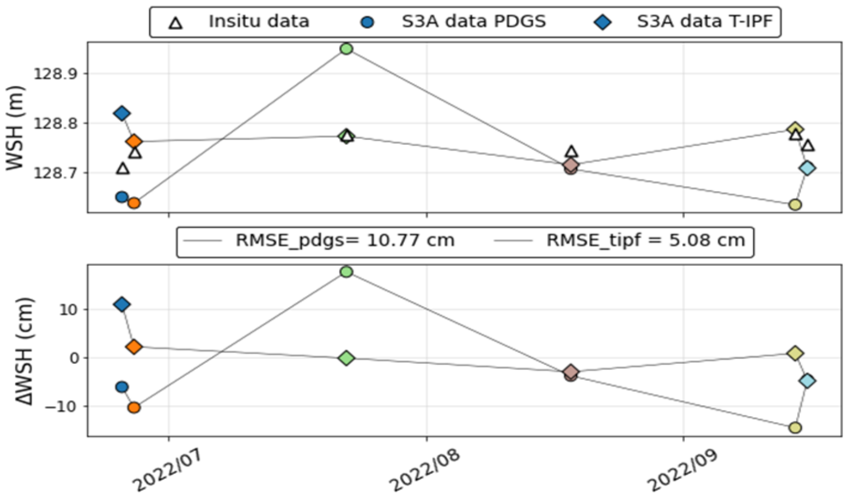


Figure 1: Example of time series of the comparisons of S3A PDGS and S3A Thematic Hydro products with in-situ data over Canal du Midi with Trèbes in Situ data. Top = WSH, Bottom = Difference with respect to in-situ data.

With algorithmic improvements, such as Hamming filtering, associated with the Thematic Hydro products with respect to PDGS Land products, the altimeter better focuses on the SAR band. Impact of the orientation of the water body with respect to the SAR band direction, particularly for rivers due to their elongated shape and their slope, is then expected to have a larger impact. Indeed, the slope of the echogenic surface induces POCA displacement as presented in the Aisne River study case. Figure 2 presents the distribution of the slope at virtual stations positions in two datasets of interest: the median slope at the position of Copernicus Global Land S3A stations is of 35cm/km, such value is expected to induce a 5cm WSH error. In the presence of Hamming filtering, this effect is expected to affect the measurements differently depending on the angle of the river section with the SAR band. MPC recommends that the sites, at least the opportunity sites, present **various geometry configurations** of the water bodies with respect to the SAR band. Having **FRM in increasing complexity** sites is a necessity to understand and provide the error budget.

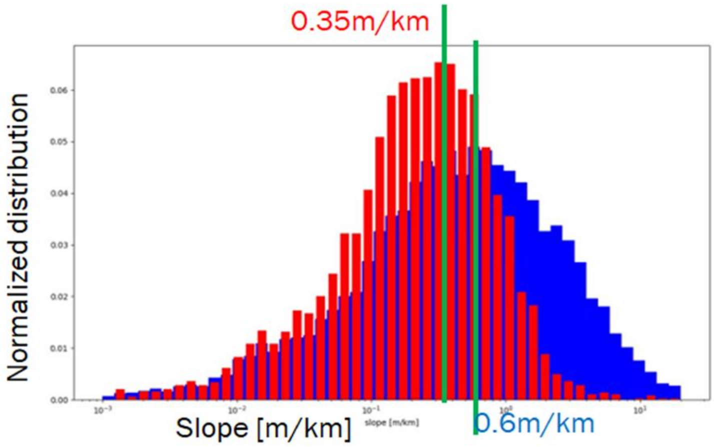


Figure 2: Distribution of the river slope at virtual station (VS) positions in Copernicus Global Land S3A VS dataset (red) and in SWORD database at the positions of S3A theoretical ground track (blue)

Eventually another challenge in valorising altimetry data is being able to disentangle in between the signal of multiple water bodies. MPC activities also aim at validating potential future evolutions of the products, the validation of fully-focus SAR products is among them. It has been shown ([RD14] and [RD15]) that FFSAR waveforms can be contaminated with spurious replicas. A means of better understanding these products over inland waters and validating them would be to **equip**, with in-situ WSH measurement means, **several water bodies that fall within the altimeter footprint** over a few sites. Ideally, considering several sites with various river widths from a few tens of metres to few hundred metres would be of great interest to study the contamination by surrounding echogenic elements, and/or by spurious replicas as a function of water bodies size.

2.2. Recommendations from the CCVS project

The objective of the Copernicus Cal/Val Solution (CCVS, CCVS | toward a Copernicus Cal/Val Solution) is to define a holistic solution for all Copernicus Sentinel missions (either operational or planned) to overcome current limitations of Calibration and Validation (Cal/Val) activities. Operational Cal/Val is required to ensure the quality of and build confidence in Copernicus data. However, these activities are currently limited by the following considerations:

- The requirements and objectives need to be revisited to consider new usage of Copernicus products, inter-operability requirements, and to anticipate the needs of future Copernicus missions
- Current Cal/Val activities are constrained by programmatic and budgetary requirements and do not necessarily follow scientific priorities
- Cal/Val activities depend on the operational availability of high-quality Fiducial Reference Measurements (FRM) which are today mostly provided by external entities without strong commitment to the Copernicus program
- Synergies within Copernicus and with other national and international programs are not systematically explored.

To address these limitations CCVS will propose:

- An updated specification of Cal/Val requirements for the Sentinel missions, taking into account inter-operability needs
- An overview of existing Calibration and Validation sources and means
- A gap analysis identifying missing elements and required developments in terms of technologies and instrumentation, Cal/Val methods, instrumented sites and dissemination service.
- A comprehensive Copernicus Cal/Val Solution to organize the long-term provision of FRM for Sentinel missions
- A roadmap documenting how the Cal/Val Solution can be implemented, highlighting responsibility, cost and schedule aspects. This plan will be elaborated in concertation with all stakeholders through four Working Groups gathering European Space Agencies, Copernicus Services, measurement networks and International partners.

In this framework the report dedicated to satellite altimetry Cal/Val [RD26] demonstrate that in situ FRM is one of the 3 pillars of Cal/Val activities as illustrated in Figure 3.

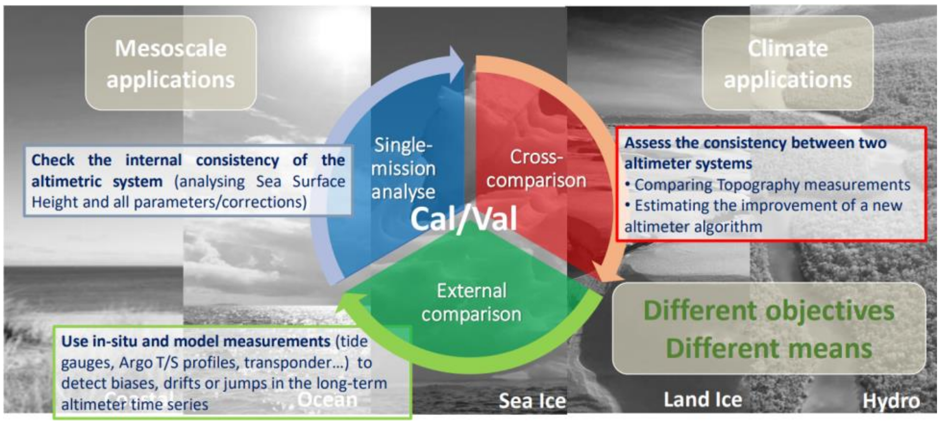


Figure 3: Pillars for altimetry validation activities

This report mention that for inland waters, the review of the requirements provided in the CalVal Plan, proposes to measure the tracking performances (or OLTC precision when operating in Open Loop), the Water Surface Height (WSH) precision and accuracy for different kind of targets (rivers, lakes, estuaries,…), of different sizes, compare the results with past and existing missions and finally propose an assessment of other variables such as wind speed, SWH over specific (large) surfaces.

The proposed roadmap is in line with these recommendations to provide Fiducial Reference Measurement of water surface height on different kind of targets and of different sizes for the performance analysis of the Sentinel-3 data products.

In addition to this report, the CCVS projects also delivered a specific report on the Copernicus CalVal Solution [RD27] providing recommendations to the CalVal means for each earth observation techniques of the Copernicus constellation and on each surface. This report emphasises the better validation status for the larger targets (large lakes and the largest rivers) which is mainly driven by a better representativeness and data quality of the reference data sets that can be used compared to the smaller water bodies as illustrated in Figure 4.

WSH (Water Surface Height)	Ref. Data Representativeness				Ref. Data quality				Validation Method				Validation results				Overall
	In-situ	Inter-sat	Models	Alternative process	In-situ	Inter-sat	Models	Alternative process	In-situ	Inter-sat	Models	Alternative process	In-situ	Inter-sat	Models	Alternative process	global score
WSH (Lakes and large rivers)	Good	Good	Poor	Good	Excellent	Excellent	Poor	Excellent	Good	Good	Poor	Good	Excellent	Excellent	Poor	Excellent	Good
WSH (Small lakes and rivers)	Poor	Poor	Poor	Poor	Excellent	Good	Poor	Good	Good	Good	Poor	Good	Poor	Poor	Poor	Poor	Poor

Figure 4: Product validation status for Inland Water from the CCVS project

The report notes that smaller rivers are likely to present larger slopes, making the altimetric water level estimates comparisons to nearby in situ gauges more sensitive to biases induced by the height (slope times distance) in between the virtual station and in situ measurement. Smaller water bodies also have a lower contribution in terms of the backscattered signal compared to surrounding echogenic targets (other water bodies, sand benches, anthropic reflective surfaces), making their contribution more difficult to disentangle in the altimetric waveforms, results are much more ‘environmental’ dependant for small water targets, leading to lower representativeness.

The strategy for the operational FRM provision for inland water proposed in this document account for these remarks and propose relevant solutions to tackle the slope/topography issues, the lower representativeness of small water bodies and the issues with the distance between the virtual station and the in situ measurement.

2.3. Strategy principle

In this chapter we define the strategy to provide operational Fiducial Reference Measurement (FRM) over inland water bodies. This strategy has been designed to be routinely and operationally performed with affordable costs and meeting the FRM needs in terms of quality, uncertainty, and traceability.

As described in TD-1 [RD6], the approach in the frame of this project is focused on Cal/Val super sites, completed using existing networks over various surfaces. The objective is to define reference Cal/Val sites called Cal/Val super sites based on the following criteria:

- hydrological characteristics
- one or several Sentinel-3A and/or Sentinel-3B virtual stations in a restricted area (Sentinel-6 or other flying altimeter missions can be accounted for)
- geometry (orientation) of water body with respect to the Sentinel-3 track(s)
- potential crossovers with other missions (especially with Sentinel-6, but also CryoSat, SWOT, Icesat-2)
- presence of historical and/or existing in-situ data in the area
- ease of installation of additional sensors

These reference sites are used as golden sites and have been equipped with all instruments needed to ensure operational FRM provision over a long-term period with affordable cost effort and accounting for the water surface topography and the specific properties of the area. With this approach, a limited number of Cal/Val super sites have been selected mainly in Europe (Maroni site in French Guyana has also been instrumented to build and federate the international user community, and other sites implemented for SWOT mission have inherited from TD-1 [RD6] recommendations). These sites will allow an in-depth understanding of inland water altimetry measurements, analyse the quality of the Sentinel-3 inland operational water products, the one delivered by Copernicus Land Service and contribute to the improvement of the ground segment processing. We propose a set of Cal/Val super-sites to perform in-depth analysis on a representative sample of different river and lake cases. For rivers, the proposed super sites allow to analyse rivers of different widths, with simple (canals) and complex topography (Garonne, Po), slow or dynamic temporal variations and with different measurement geometries (from perpendicular to parallel). For Cal/Val activities it is important to have different sites with different configurations (both in terms of hydrological properties and crossing geometries with Sentinel-3 orbits), in this context we do not recommend having a limited number of Cal/Val super sites. The more we have, the better it is for Cal/Val purposes. So, any new Cal/Val super site will be welcome. In order to have a representative set of cases, a number of 40 to 50 super sites would be relevant. However, and as done over the ocean surfaces, we strongly recommend pursuing the efforts on the set of super sites instrumented during this St3TART project as Cal/Val approaches require a much longer duration than the current St3TART phase.

We also propose to complete this strategy with opportunity sites based on existing in-situ networks combined with activities to make existing measurements meet the FRM requirements when possible. The resulting FRM provisioning strategy scheme is presented in Figure 5.

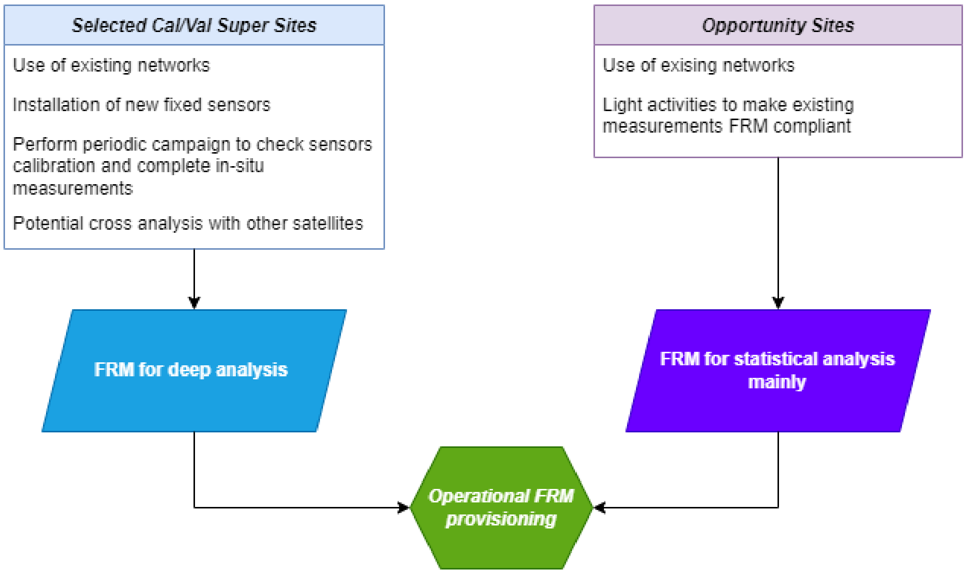


Figure 5: FRM provisioning strategy.

Of course, statistical analysis will be performed on Cal/Val Super Sites in addition to the deep analysis.

This roadmap for Cal/Val of Sentinel-3 measurements over hydrological areas is in line with the Sentinel-3 MRTD [RD12]. With the proposed strategy, Cal/Val activities will be able to evaluate the Sentinel-3 performances according to the requirement S3-MR-180 from [RD12], which states that "Sentinel-3 shall provide measurements of River and Lake Heights (RLH) for large rivers, their tributaries and lakes to at least the quality of the RA-2 on ENVISAT", and also the requirement S3-MR-1200: "Sentinel-3 shall provide River and Lake Hydrology (RLH) and River and Lake Altimetry (RLA, containing individual retracked radar echo waveforms) products shall be delivered to the hydrological services in a timely and operational manner."

In this context, the roadmap presented in this document will allow to ensure the operational provision of Fiducial Reference Measurement to perform Cal/Val activities of Sentinel-3 (among other missions), and to fulfil the mission requirements concerning river and lake heights. The provision of FRM for inland waters will also serve scientific and hydrological interest and ensure performance evaluation of future Algorithm Processing Baseline evolutions.

2.4. Sensors

Based on the sensor review made in the TD-1 document [RD6], almost all sensor types analysed are precise enough to be used for operational FRM provisioning, as long as regular calibration activities are performed, at least twice a year. But all sensors are not equivalent in terms of ease of installation, of operationality and of data transmission and remote-control capability.

In the frame of the St3TART project and depending on the site configuration and infrastructure, we have made use of the following sensors:

- vorteX.io micro-stations
- pressure sensors
- radar sensors
- Cyclopée acoustic altimeter
- CalNaGeo towed GNSS carpet
- vorteX.io drone-embedded LiDAR

Moreover, it has been demonstrated in the TD-1 [RD6] that surface roughness and the actual satellite overflight track are strong contributors to the uncertainty of altimetry measurements over inland water. It is also important to evaluate the performance and the behaviour of the different in-situ sensors with respect to surface roughness evolution.

In order to meet FRM requirements we have performed sensor performance analysis (see TD-1 [RD6]) in a test basin to evaluate the capability and the absolute uncertainty of the sensors that will be used in the project. The objective of this experiment was to establish the relation between the measured height and the actual height as a function of the surface roughness variation. The test basin of Marseille-Luminy (LASIF) has been used for this experiment. The Marseille-Luminy wind wave facility is known by the scientific community working in the fields of air-sea interactions and marine technologies as a unique installation owing to its large dimensions and the exceptional quality of the air and water flows respectively generated in the wind tunnel and the water tank (at least in France). The facility is extensively used for measuring air-water surface fluxes in realistic sea conditions (momentum, energy, mass and gas exchanges), investigating small-scale wind wave roughness and the associated acoustic and electromagnetic wave backscattering at the water surface and more recently, characterising the aerodynamic and hydrodynamic responses of marine structures as floating wind turbines.

2.5. Cal/Val super sites

In the TD-1 document, we have demonstrated that each site is different depending on its geography, water surface topography, geometry with the satellite track and the hydrological context. It is thus impossible to propose the provision of the same operational FRM equipment for all Sentinel-3A or Sentinel-3B virtual stations covering an inland water body or an estuary. All sites need to be selected with a lot of care and the instrumentation to be installed is site dependent. Indeed, this is also a lesson learnt from the Ocean super sites installed by the different teams: one needs to account for the local constraints, and if there is some generic process to follow, the selection of sensors needs to be adapted to the site characteristics.

Following the strategy described in chapter 2.1, Cal/Val super sites are identified and selected within different inland water bodies, where all instruments needed to tackle the different uncertainty contributors to the water surface height measurement have been installed. The objective was to have a set of reference sites providing operational FRM with long-term support and with different hydrological characteristics. Cal/Val super sites must ensure the validation of the Sentinel-3 data products over inland waters on this long-term basis, including future missions such as Sentinel-3C and, of course, Sentinel-6 virtual station. Those sites will also be important for the validation of future missions like CRISTAL and could be valuable for old missions like ENVISAT. Indeed, it has been demonstrated several times in the past that R&D activities and new reference data provide a new perspective on the behaviour and issues of past missions.

These Cal/Val super sites are clearly mandatory for rivers, where the impact of the surrounding environment, the water topography of the river and its variation in time must be analysed and measured precisely to meet FRM requirements and provide uncertainty and traceability required by FRM. Indeed, it has been demonstrated by Sandwell and Smith [Sandwell & Smith 2014][RD8] that the Point Of Closest Approach (POCA) moves from the nadir position depending on the slope of the water surface, knowing that the slope values are not constant along rivers. Thus, the height error due to this slope effect can reach several centimetres as shown in Figure 6 and Figure 7. In addition, as the position of the satellite track moves from cycle to cycle within +/- 1 km [RD6] of the reference ground track, the POCA will move from cycle to cycle according to the position of the track and the variation in the slope/landform of the river. It is thus mandatory to have regular measurements of this slope or to build a slope variation chart to properly know where the actual satellite measurement is located. This slope measurements must be provided as a product of FRM measurements over rivers.

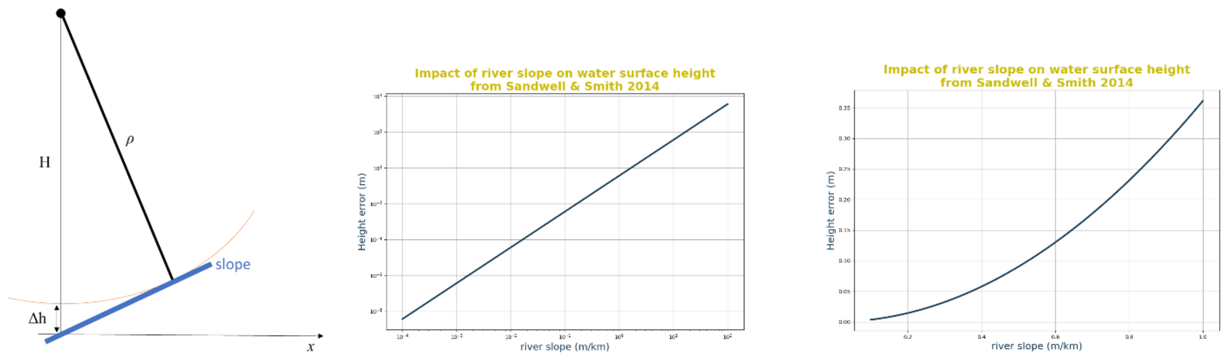


Figure 6: Geometry of the altimetry measurements over a river slope (left), impact of river slope on water surface height measured by satellite altimetry computed from Sandwell & Smith (centre) and zoom on some specific river slope values (right).

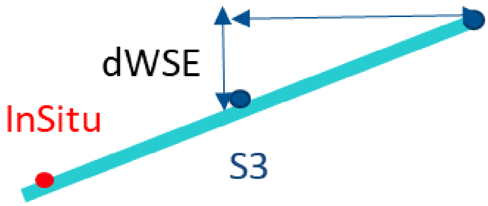


Figure 7: Scheme of the river slope impact for Cal/Val over river with a permanent in-situ sensor

For rivers, we selected the following Cal/Val super sites in the frame of the project:

- Garonne river near Marmande in Southern France which is a very interesting site representative of medium-width rivers (about 150 m) with a strong height dynamic and a challenging water topography. This site is also of interest because of the multiple crossovers of 2 Sentinel-3A ground tracks along a 15 km-long segment in addition to a Sentinel-6 crossover and the fact that Sentinel-6-MF is quite parallel to the river over about 15 km. This river mostly has an orientation South-East → North-West
- Canal du Midi near Trèbes in the South of France which is an ideal case for Sentinel-3 measurements. This site is a thin, flat and controlled canal crossed by a Sentinel-3A track perpendicular. With these conditions, we will be able to measure the performance of the Radar altimeter and potentially get an uncertainty driven by the instrument uncertainty. This site has been also selected because a bridge is located just below the Sentinel-3 ground track, which facilitates the installation of an in-situ sensor.
- Rhine river in France near Strasbourg and in several places in Germany: it is a large river with a strong hydraulic control, which leads to a succession of flat-water surface segments with a very small slope, separated by jumps of different altitudes. Jumps can reach a height of several metres. This river is mainly oriented South → North.
- Po river in Italy: selected for its East-West geometry allowing multiple high-angle crossings, with Sentinel-3 tracks. The main river width ranges from 200 m to nearly 500 m. In light of its geometrical characteristics and the amount of available hydrological observations, the Po River represents an ideal test case for the validation of altimetry satellite missions.
- Tiber river in Italy: selected for its North-South geometry and its width of the order of 50-80 m only.
- Maroni river in French Guiana, which is interesting to open the St3TART project outside European borders to federate communities around the FRM provision over inland water, and to cover a tropical situation which is very different from the mid-latitude situations encountered in Europe.

Concerning lakes and reservoirs, super sites are important to measure geoid errors over big lakes, to account for the actual differences between the altimeter measurement performed in the middle of the lakes and that obtained from the sensors at the lake shore and the roughness impacts. The work performed in TD-1 showed that surface roughness can have a strong impact on the altimeter signal. As surface roughness over lakes is mainly due to the wind stress, a wind speed measurement must be provided. This wind sensor might not be enough as the wind generates local stress effects on the water surfaces that are highly dependent on the surrounding topography and wind intensity. To perform an actual measurement of the surface roughness during the satellite overflight, an automatic vehicle (UAV) could/should be deployed but this sensor device is not available at the time of writing. For lakes, we propose to rely more systematically on existing in-situ networks. Indeed, it has been shown in TD-1 [RD6] that several existing in-situ sensor networks over lakes allow easy access to their near real-time measurements, and are well maintained and of good quality, notably in Switzerland, Norway, USA and Denmark (among many other places). We therefore propose to use such existing networks and to perform periodic campaigns for regular calibrations with moving sensors such as drone-embedded LiDAR or towed GNSS carpet in order to improve the knowledge of the local geoid and to check the calibration of existing in-situ sensors. The roughness impact must be monitored through wind speed measurements that must be collected around lakes.

In this context, the selected Cal/Val super site over lakes is limited to one unique site, Issykkul Lake, where a lot of analysis has been conducted for many years and where a lot of activities will be conducted in the framework of the SWOT Cal/Val phase. In addition to this super site, and as demonstrated in TD-1 [RD6], the use of the opportunity site is particularly reliable on lakes and will therefore be widely used.

For Lakes, the selected Cal/Val super site are the following:

- The Issykkul Lake which has been studied for many years and is well known and well instrumented.
- All lake targets with a reliable, well-maintained sensor from the existing networks with a Sentinel-3 ground track crossing the lake.

2.6. Opportunity Cal/Val sites

To complement super sites and increase the number of FRM sites over inland water, with limited costs, it is interesting to take advantage of existing in-situ networks when the measurement stations are located less than 150 m from the satellite reference ground track (as a first guess), but this distance can be increased if the local slope is small or well characterized. Indeed, thanks to the different national in-situ networks, which are mostly public and free to use, the opportunity must be analysed to consider as an opportunity Cal/Val site for operational FRM provision a site where in-situ measurements are:

- located below a Sentinel-3 track (or Sentinel-6) at less than 150 m from the satellite reference ground track. Some sites can be selected at a higher distance if they have small or well-characterized slope (e.g., for relatively small lakes that can be assumed to be flat).
- easy to access: data shall be easy to collect in order to meet the reliable timeliness requirement
- data available within a 28-day latency
- traceable: clear information on sensors, data processing, calibration and positioning must be available to meet the requirements of the metrological approach.
- well georeferenced: georeferencing shall be assessed with external data (IceSat-2, other satellites measurements, in-situ means, bibliography, etc.).
- not requiring strong effort to make FRM compliant, following requirements written in TD-1 [RD6].

If all the conditions listed above are met, the site can be used and selected as an opportunity Cal/Val site for operational FRM provision. Depending on the site characteristics, additional instrumentation or calibration as listed below can be installed at moderate cost:

- installing an automatic station (vorteX.io micro-station)
- and/or installing a citizen science system (plain rule installed, citizens provide water height by reading the rule)
- and/or performing a precise georeferencing of the existing in-situ sensor.

It is important to note that the selection of opportunity sites will be done on a case-by-case basis due to the different problems that are encountered as soon as existing in-situ systems are considered. Indeed, a lot of systems installed by national or local authorities are dedicated to flood risk monitoring and are not well georeferenced (or not georeferenced at all) and they only provide a relative water surface height. The sensors dedicated to flood risk are not calibrated on a regular basis either, which is an important issue to meet FRM requirements. Some of the existing networks are also not well maintained which is a strong problem for long term usage. Finally, there are existing in-situ stations that have been installed by local companies (energy suppliers, water companies, etc.) and for which it will be very difficult, if not impossible, to access and retrieve the data regularly.

2.7. Federate the hydrological community

2.7.1. Collaboration with the European Environment Agency

The European Environment Agency (EEA, https://www.eea.europa.eu/en) is an agency of the European Union that delivers knowledge and data to support Europe's environment and climate goals. The core tasks of the EEA are defined in the founding EU regulation and include:

- supporting policy development and key global processes;
- offering analytical expertise;
- providing and maintaining an efficient reporting infrastructure for national and international data flows.

In collaboration with the partner network, Eionet, EEA informs decision-makers and the public about the state of Europe’s environment, climate change and wider sustainability issues.

The EEA is currently working in the H2020 COINS project (Copernicus In Situ, https://insitu.copernicus.eu/) with different activity. A meeting with the team in charge of the hydrology activities has been performed in order to exchange on the potential collaboration between this project, EEA and the needs of the St3TART project. The COINS project aims to:

- **Determine the state of play:** maintain an overview of Copernicus' in situ data requirements, use, and challenges.
- **Provide access to data:** establish, maintain, and improve operational provision of selected in situ data in accordance with the Entrusted Entities' needs.
- **Engage with data providers:** engage and create partnership and other agreements with in situ data providers, networks, and organisations to improve in situ data access and use conditions in accordance with Copernicus' needs.
- **Engage with data providers:** engage and create partnership and other agreements with in situ data providers, networks, and organisations to improve in situ data access and use conditions in accordance with Copernicus' needs.

It has been decided during the meeting that the COINS project and EEA will facilitate the access to in situ data from the different national providers contributing to EEA and Eionet (The European Environment Information and Observation Network). In this context, contacting EEA and the COINS project to access to new public national networks is warmly recommended for the need of the opportunity sites over Europe.

In this framework, a report has been released on the hydrological data requirements for Copernicus. The report was prepared by a group of experts for the European Environment Agency, coordinating the Copernicus Programme In Situ Component [RD25]. In situ data are essential for the validation of satellite datasets and are routinely used in the production and validation of Copernicus products. This report identifies the data needs for the development of hydrological outputs from the Copernicus programme, assesses gaps in the availability of these data, and proposes coordination mechanisms to improve the availability. Addressed are the measurements of river levels and flows, lake levels, river water quality, lake water quality (including temperature), and soil moisture.

Several Copernicus services use hydrological data collected by national regulatory agencies with some measurements undertaken only within research activities. The European Flood Awareness System (EFAS) delivered by the Copernicus Emergency Management Service (CEMS) extensively uses river flows and levels data. CEMS maintains a dedicated data centre to collate and quality control these data from national agencies. The Copernicus In Situ Component coordinated by the EEA is working with the EFAS hydrological data collection centre to improve the licensing under which this data is acquired and to help this data be of wider use across the Copernicus Services within the development of other products.

The Copernicus Land Monitoring Service (CLMS) river level products will particularly benefit from these hydrological data as the availability of near real time river levels is limited at both European and global scales. CLMS and the Copernicus Marine Environment Monitoring Service (CMEMS) are both working on satellite products to improve understanding of coastal zones and will need river flow and water quality data. The report suggests that the national agencies should adapt their statutory monitoring strategies to acquire the in situ data needed for satellite monitoring.

The St3TART project and the roadmap proposed here is perfectly in line with these recommendations.

2.7.2. Open call system

It is important to underline that this ESA initiative is mainly addressed to European countries and aims at federating the hydrological community to contribute to the provision of FRM following this roadmap.

In this context, an open call system (Announcement of Opportunity call) should be defined based on this roadmap for implementing new opportunity site. It is important to note that a long time is required to evaluate and qualify a site (validate the instrument choices, the location of each instrument, analyse the seasonal effects, etc). It is therefore important to account for the long-term operational needs in these open calls. These open calls shall account for the opportunity site requirements listed in section 2.6.

2.8. Classification of Cal/Val sites

As mentioned above, each Cal/Val sites is different from one to another due to the hydrological characteristics, the surrounding terrain, the crossing geometry with Sentinel-3 ground tacks or the ease of installing instrumentation in the field. The objective of this document is to provide a roadmap for performing the operational provision of Fiducial Reference Measurements (FRM) to support operational Cal/Val activities.

In this context, it is important to identify categories between Cal/Val sites depending on:

- Hydrological properties of the inland water body
- Crossing geometry with Sentinel-3 ground tracks.
- Location of the in-situ sensors

The chosen convention is to classify Cal/Val sites depending on the complexity to provide/compute FRM for Sentinel-3 Cal/Val activities accounting for the 3 points mentioned above.

Following this convention, 4 classes have been defined: Complexity Level 0 (CL0), Complexity Level 1 (CL1), Complexity Level 2 (CL2) and Complexity Level 3 (CL3), from the “simplest” case to the “most complex”. It is important to note that for sites where the river and the satellite track are collinear, the Complexity Level can change from a CL0 to a CL1, CL2 or CL3 depending on the hydrological properties of the inland water body and with the increasing distance between the actual satellite measurement and the reference in-situ station.

It is worth to mention that this classification is valid for Cal/Val super sites for both rivers and lakes. The strategy for opportunity sites is to only consider Complexity Level 0 to ease the automatic processing for the statistical analysis.

2.8.1. Complexity Level 0 sites

Complexity Level 0 sites correspond to the simplest case for the FRM provision.

Characteristics:

- The in-situ sensor is installed/located just under the Sentinel-3 ground track (inside the orbit excursion area which corresponds to a +/- 1 km around the Sentinel-3 reference ground track)
- Water bodies with no or very moderate slope (small lakes, reservoirs, canals…)

Additional data:

- No external data is needed.

The FRM measurement:

- Ideally, the in-situ measurement must be synchronised with the satellite pass (in-situ measurement performed at the same time as the satellite measurement). If not possible, a workaround can be found by interpolating between 2 in-situ measurements at the time of the satellite overflight.
- The FRM measurement corresponds to the measurement of the in-situ sensor (IS), levelled with respect to the reference ellipsoid: $\boldsymbol{WSH_{FRM}(t) = WSH_{IS}(t)}$
- The FRM uncertainty corresponds to the sensor uncertainty.

2.8.2. Complexity Level 1 sites

Complexity Level 1 sites correspond to Cal/Val sites where in-situ sensors are not located under the Sentinel-3 ground track (distance between the in-situ sensor and the actual satellite ground track longer than 1 km), with a steady water surface of the water body and no variation in time of the slope of the water body (like a canal or the effect of the geoid over a lake).

Characteristics:

- The in-situ sensor is not installed under the Sentinel-3 ground track (distance between the in-situ sensor and the actual Sentinel-3 ground track > 500m)
- The water body topography is not dynamic, and the slope or river profile is not evolving with the water level. Example: a canal with a linear controlled slope or the geoid effect over a lake.

Additional data:

- The slope of the water body must be measured by a moving sensor or, if possible, ICESAT-2, or 2 in-situ sensors in case of a canal

The FRM measurement:

- Ideally, the in-situ measurement must be synchronised with the satellite pass (in-situ measurement performed at the same time as the satellite measurement). If not possible, a workaround can be found by interpolating between 2 in-situ measurements at the time of the satellite overflight.
- The FRM measurement corresponds to the measurement of the in-situ sensor (IS), levelled with respect to the reference ellipsoid and corrected from the slope effect: $WSH_{FRM}(t) = WSH_{IS}(t) + Slope$
- The FRM uncertainty corresponds to the in-situ sensor uncertainty combined with the slope measurement uncertainty.

2.8.3. Complexity Level 2 sites

Complexity Level 2 sites correspond to Cal/Val sites where in-situ sensors are not located under the Sentinel-3 ground track (distance between the in-situ sensor and the actual satellite ground track longer than 1 km), with a dynamic water surface of the water body but no variation of the slope whatever the water level.

Characteristics:

- The in-situ sensor is not installed under the Sentinel-3 ground track (distance between the in-situ sensor and the actual Sentinel-3 ground track > 500m)
- The water body topography is dynamic, a propagation time must be accounted for between the position of the in-situ sensor the position of the Sentinel-3 ground track
- The slope (geoid effect on a lake) or river profile is not evolving with the water level

Additional data:

- The slope of the water body must be measured by a moving sensor or, if possible, ICESAT-2, or 2 in-situ sensors in case of a canal
- A second in-situ sensor is mandatory to measure the propagation time. The Sentinel-3 virtual station must be located between the 2 in-situ sensors

The FRM measurement:

- The propagation time δt must be accounted for when considering the measurement from the in-situ sensor. This propagation time must be computed using the 2 in-situ sensors located on both side of the Sentinel-3 virtual station
- The slope of the water body must be accounted for between the position of the in-situ sensor and the Sentinel-3 virtual station
- The FRM measurement corresponds to the measurement of the in-situ sensor at the time of the satellite overflight t plus the propagation time δt corrected from the slope effect: $WSH_{FRM}(t) = WSH_{IS}(t + \delta t) + Slope$
- The FRM uncertainty corresponds to the combination of the in-situ sensor uncertainty, the slope measurement uncertainty (moving sensor) and the propagation time uncertainty

2.8.4. Complexity Level 3 sites

Complexity Level 3 sites correspond to Cal/Val sites where in-situ sensors are not located under the Sentinel-3 ground track (distance between the in-situ sensor and the actual satellite ground track longer than 1 km), with a dynamic water surface of the water body and a complex topography, the slope evolving with the water level.

Characteristics:

- The in-situ sensor is not installed under the Sentinel-3 ground track (distance between the in-situ sensor and the actual Sentinel-3 ground track > 500m)
- The water body topography is dynamic, a propagation time must be accounted for between the position of the in-situ sensor the position of the Sentinel-3 ground track
- The water topography is complex and evolving with the water level

Additional data:

- The slope of the water body must be measured at 3 different water levels (low, medium, and high) by a moving sensor
- A second in-situ sensor is mandatory to measure the propagation time. The Sentinel-3 virtual station must be located between the 2 in-situ sensors

The FRM measurement:

- The propagation time δt must be accounted for when considering the measurement from the in-situ sensor. This propagation time must be computed using the 2 in-situ sensors located on both side of the Sentinel-3 virtual station
- The slope of the water body must be accounted for between the position of the in-situ sensor and the Sentinel-3 virtual station
- The slope should be interpolated between the 3 mobile sensor profiles at the water level value corresponding to the time of the Sentinel-3 overflight, assuming that a certain water level value was assigned to each of the 3 profiles at the time t_c of their respective campaign.
- The FRM measurement corresponds to the measurement of the in-situ sensor at the time of the satellite overflight t plus the propagation time δt corrected from the slope effect interpolated at the corresponding water level: $WSH_{FRM}(t) = WSH_{IS}(t + \delta t) + Slope(WSH_{IS}(t_c))$
- The FRM uncertainty corresponds to the combination of the in-situ sensor uncertainty, the slope measurement uncertainty (moving sensor), the propagation time uncertainty, and the slope interpolation uncertainty

2.8.5. Summary of the classification

Table 1 summarises the site classification, the characteristics of each class and the associated FRM equation. The Cal/Val super sites selected in the framework of the St3TART project have been distributed among the different classes in the last row.

For all sites, it is worth to mention that surrounding water bodies can disturb the satellite measurements and can then reduce to 0 the interest of such Cal/Val sites. Depending on the objective of the Cal/Val site, it is important to consider the importance of the surrounding water bodies. If the site is dedicated to analysing the performance of Sentinel-3 measurements over a specific inland water target, then it is important to select sites without any surrounding water bodies present in the SRAL footprint.

	CL0	CL1	CL2	CL3
Characteristics	- Located under satellite ground track - No slope correction - No propagation time correction	-Not necessarily located under satellite ground track - No propagation time correction - Slope correction but not dependent on the water height	- Not necessarily located under satellite ground track - Propagation time correction - Slope correction but not dependent on the water height	- Not necessarily located under satellite ground track - Propagation time correction - Slope correction evolving with the water height
FRM equation	$WSH_{IS}(t)$	$WSH_{IS}(t) + Slope$	$WSH_{IS}(t+\delta t) + Slope$	$WSH_{IS}(t+\delta t) + Slope$
Cal/Val sites	Trèbes, Po River (Isola Pescaroli for S3B), Tiber River (Santa Lucia)	Grand Canal d'Alsace (French part of the Rhine River)	German Rhine	Garonne River, Po River, Tiber River

Table 1: Summary of the site classification

Finally, no particular recommendation can be made on the distribution of sites between the different classes. These classes have been defined to provide a calculation of the different FRMs depending on the context but do not prejudge the quality of a site. It is quite possible that a Class 4 site will provide better results than a Class 0 site. We simply recommend here to have a distribution between the different classes consistent with reality to have metrics representative of the satellite performances.

2.8.6. Harmonisation between sites

The strategy proposed in this document is also a guarantee of the harmonisation in the FRM products delivered operationally. In this context, the consistency of FRM operationally delivered is ensured by the protocols, procedures and standard FRM processing described in this document. The FRM provision must be ensured by the methods and processing defined in this document and by a uniform FRM processing that has been published on a GitHub (st3tart/fidji_mockup.ipynb at main · jcpoisson/st3tart · GitHub) in order to align the different cases. This processing must be maintained and improved in the future to account for all new site characteristics. Associated uncertainty provided to each FRM and computed following the metrological approach of chapter 6 is also mandatory for each site.

3. Cal/Val super sites over rivers

3.1. Introduction on the rationale

For river super sites, the recommended solution combines permanent sensors and periodic campaigns. The solution is described by the scheme in Figure 8. The objective is to equip the site with automatic and connected stations as close as possible to the reference ground track or covering the actual track variations. The number of stations will depend on the river topography, its variation, and the available location and infrastructure on site to install automatic stations. If the river topography is as simple as a small, linear slope in case of a segment with channel-like behaviour, two automatic stations are enough, one at each end of the segment. In this case, it is not mandatory to install stations within this +/- 1 km area even if it should be better. Also, if the slope is particularly low (which is for example the case for most of the main rivers like Congo, Amazon, or Rhine Channel art) the +/- 1 km constraint might be relaxed.

In case of a more complex river topography, the installation of more than 2 micro-stations is recommended, if possible within the +/- 1 km area around the reference ground track. A set of stations equally distributed and separated by a few tenths of metres would be ideal, but it is rarely possible to find infrastructure permitting this. Different sensor technologies can be used depending on the site constraints (available infrastructure, location for sensor installation, topography, risk areas, etc). On the other hand, an automatic data transmission system is required to automatically transmit data to the datahub within the 1-2-day latency required for the Cal/Val activities (required by MPC). A health monitoring system of the station is also mandatory to monitor the proper functioning of the station and to ensure the operationality.

To monitor permanent sensors, we propose to install a citizen science system (which has a very low impact in terms of cost) near the location of permanent sensors, mostly for lakes but also for some rivers. The citizen science measurements permit to detect potential drifts or failures and allow to raise awareness about hydrological issues among the citizens. Citizen science has already demonstrated its added value in the provision of high-precision measurements but also in terms of very low costs. However, citizen science cannot be used on an operational basis due to high seasonality and site dependency as explained in TD-1 [RD6].

If available, existing sensors can be used on super sites, but the quality and the compliance of the existing sensors must be checked with respect to FRM standards. A GNSS calibration can be performed on the existing sensor to properly reference the precise position and the measurement of the sensor. It is also necessary to ensure that the data is accessible on a regular basis and that the time taken to make the data available is compatible with the expected latency for operational Cal/Val activities.

In addition to these permanent sensors, periodic campaigns must be performed. These campaigns will serve 2 different purposes:

- calibration campaigns
- river topography measurement campaigns

The first purpose is to ensure the calibration of all sensors present on the super sites. It is important to check the quality of the measurements and to ensure that all measurements are comparable in the same reference system. The second purpose, as important as the first one, is to provide a measurement of the water surface topography and its evolution over time, between all sensors and the satellite virtual station locations. Indeed, the TD-1 document [RD6] has demonstrated the importance of knowing the river topography and its variation throughout the year. As the satellite ground track moves within 1 km from cycle to cycle, it is not possible to provide the height of the water surface below the satellite track at each cycle with permanent sensors, unless a sensor is installed for example every 100 metres, which is not really possible nor cost effective. It is thus mandatory to measure the water topography along the river between the permanent sensors and the satellite ground tracks. In this context, periodic campaigns must be performed at different water stages using one of the moving sensors reviewed in TD-1 [RD6]. The choice of one sensor rather than another will be done depending on the site constraints. In this project we choose to use the vorteX.io drone-embedded LiDAR altimeter, the towed GNSS carpet or Cyclopée depending on the Cal/Val sites. The objective is to build different river topography profiles at different water heights and to provide these sets of profiles to users to correct the measurement of the permanent sensor from the height difference between the actual ground track and the permanent sensors due to the distance between them.

All sensor measurements (both permanent and periodic) must be calibrated with a high-precision GNSS positioning system to provide measurements with a common reference system and comparable to the satellite measurements. In this context, it is mandatory to provide all height measurements with respect to the WGS84 reference ellipsoid as the one used by the Sentinel-3 missions. It is also mandatory to provide the associated uncertainty for each measurement.

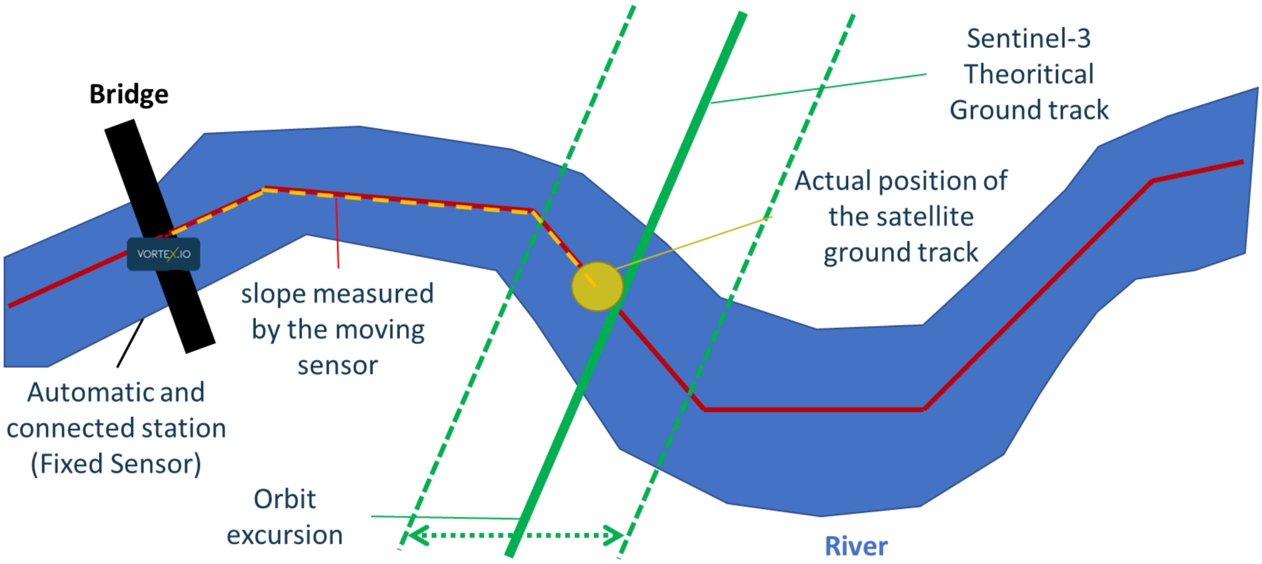


Figure 8: Scheme of Cal/Val super site instrumentation over a river

3.2. Strategy for the computation of FRM over rivers

In this chapter we propose a generic strategy to compute Fiducial Reference Measurements over rivers. Of course, depending on the site characteristics (distance between the actual nadir track position and the closest in-situ station, slope / topography of the river), the recipe can be simplified.

3.2.1. Prerequisites

Before starting to compute the FRM, it is important to first compute the following variables:

- The curvilinear abscissa to get the distance between two in-situ stations, but also to be able to compute the distance between the actual nadir track position and the closest in-situ station
- Topography or slope measurements along this curvilinear abscissa. If the river slope is linear (for example when the river segment is controlled by a lock or if the water body is a canal), then the slope is simply computed using in-situ stations by a simple difference between 2 simultaneous in-situ water surface height performed by the 2 in-situ stations and by dividing the height difference by the distance between the 2 stations.

The number of slope/topography measurements needed depends on the actual dynamics of the river. If the water level of the river changes rapidly and significantly over time, several height profiles of the river at different water levels are needed to interpolate the topography using the water level measured at the time the satellite flies over the river.

It is important to note that if the river topography is measured by mobile sensors (drone, CalNaGeo, Cyclopée, boat, etc.), then it is mandatory to correct the measurements of the mobile sensors for the water level evolution observed during the measurement of the mobile sensors. Indeed, the objective here is to measure an “instantaneous topography” which should not be impacted by the temporal variation of the water level during the campaign. To do so, in-situ stations present in the area are used to correct the time evolution of the water surface height from the moving sensor measurements during the campaign.

3.2.2. The computation of the FRM

The computation of the FRM is described in Figure 9. The objective of this strategy is to provide the in-situ water surface height at the actual nadir track position station and to ensure that the in-situ measurement has measured the same water particle as the satellite. A mockup of this processing developed in python is also provided into a github in a jupyter notebook. The github can be freely accessed here: https://github.com/jcpoisson/st3tart/blob/main/frm_mockup/fidji_mockup.ipynb. An Algorithm Baseline Theoretical Document (ATBD) will be also provided at the end of the project.

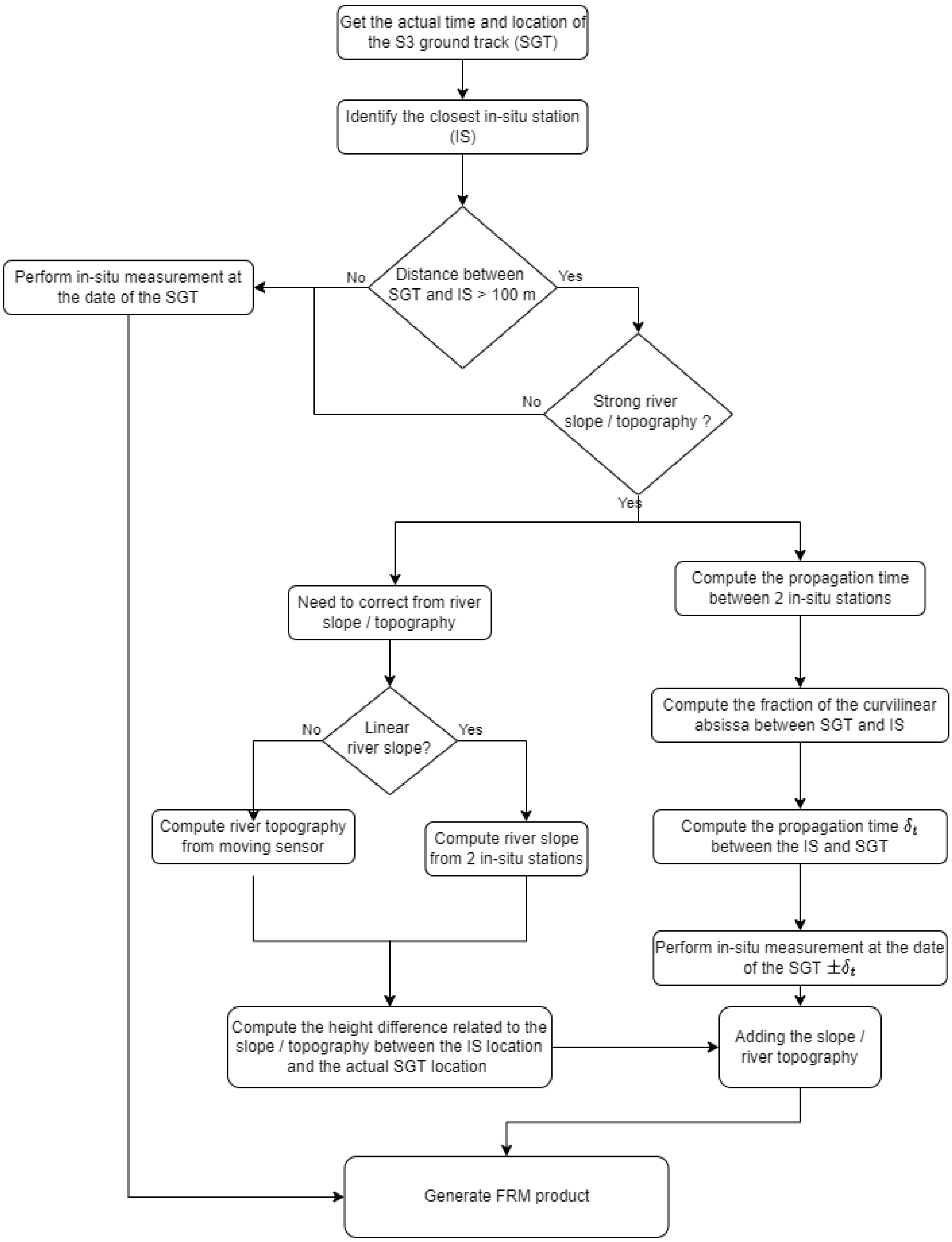


Figure 9: Scheme detailing the strategy to compute FRM over rivers

The processing described here corresponds to Figure 8 and the different steps are detailed below:

1. Based on the prerequisites, the first action consists in computing the exact position of the actual nadir track position along the curvilinear abscissa.
2. Then, the closest in-situ station (automatic and connected stations is preferred) is identified. The distance between the closest in-situ station and the actual nadir track position is computed.
3. If the actual nadir track position is located at a distance < 100 m from the in-situ station, or if the river slope is almost flat, then the FRM corresponds to the measurements of the in-situ station performed at the exact time of the satellite measurement. If a vorteX.io micro-station is used, simply set up the station so that the in-situ measurement is taken at the precise date of the satellite pass. If the in-situ station is not a micro-station, then the in-situ measurement must be interpolated to the exact time of the satellite pass. The FRM is directly generated from this measurement (jump directly to point #7).
4. If the actual nadir track position is located at a distance > 100 m from the closest in-situ station and the river slope topography is not "flat", then the river slope / topography must be accounted for.
   If the river is linear, then the river slope computed in 3.2.1 is simply multiplied by the curvilinear distance between the closest in-situ station and the actual satellite measurement.
   If the river topography is not linear, then the topography measured beforehand using moving sensor campaigns is used. If the river is dynamic (i.e. with a river slope evolving with the water level), the river topography must be interpolated between two different river topographies measured at 2 different water surface heights, using the actual water surface height measurement from the closest in-situ station. If the river slope is not dynamic, the river topography measurement is directly used. Then, the river slope is accounted for by computing the height difference on the river topography between the position of the actual nadir track position and position of the closest in-situ station. The resulting value corresponds to the topography correction.
5. Due to the distance between the closest in-situ station and the actual satellite measurement, the water propagation time must be accounted for (see Halicki et al. 2022 [RD13]) when considering the in-situ station measurement to compute the FRM. Indeed, as illustrated in Figure 10, the objective is to measure the same water particle with the in-situ station as that measured by the satellite. In this framework, the propagation time δ_{ts} must be accounted for and the in-situ measurement must be considered at the exact date of the satellite measurement +/- δ_{ts} (+ if the in-situ station is located downstream of the satellite measurement, - if the in-situ station is located upstream).
   This propagation time is computed using 2 in-situ stations (1 upstream and 1 downstream of the actual nadir track position) and using their measurements performed during few days before the date of the actual satellite measurement:
   a. First the propagation time δ_{ti} between the 2 in-situ stations. To do so, 5 days of water surface height measurements from both stations are considered. From these two timeseries, we apply a Nelder-Mead algorithm to minimize a least square criterion to find the propagation time δ_{ti} between the two stations. This computation can be performed using anomaly instead of using their absolute measurements (the average value is subtracted to both stations). If the propagation time is properly estimated with a high degree of confidence (minimizing the least square criterion and with a maximum correlation value), the two time series are synchronized when the δ_{ti} is applied to one station as shown in Figure 11, where the δ_{ti} has been computed and applied to the micro-station called "le-mas-d-agenais_1" in dashed blue and compared to the "marmande_1" station over the Garonne River.
   b. Then the propagation time δ_{ts} is computed from a fraction of the δ_{ti}. This fraction is simply the ratio between the two curvilinear distances, assuming that the velocity is constant.
6. The FRM measurements is then computed from the closest in-situ station measurement taken at t+ δ_{ti} and corrected from the slope / topography correction computed in point #4. If a vorteX.io micro-station is used, simply set up the station so that the in-situ measurement is taken at the precise date of the satellite pass + δ_{ti}. If the in-situ station is not a micro-station, then the in-situ measurement must be interpolated at the exact time of the satellite pass + δ_{ti}.
7. The FRM product is then generated in NetCDF format.

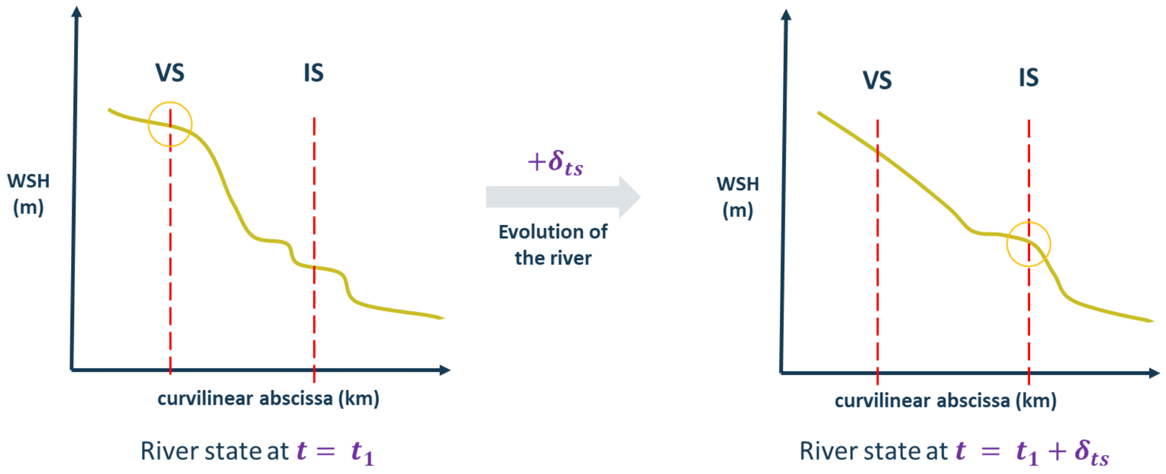


Figure 10: Diagram explaining the propagation time issue

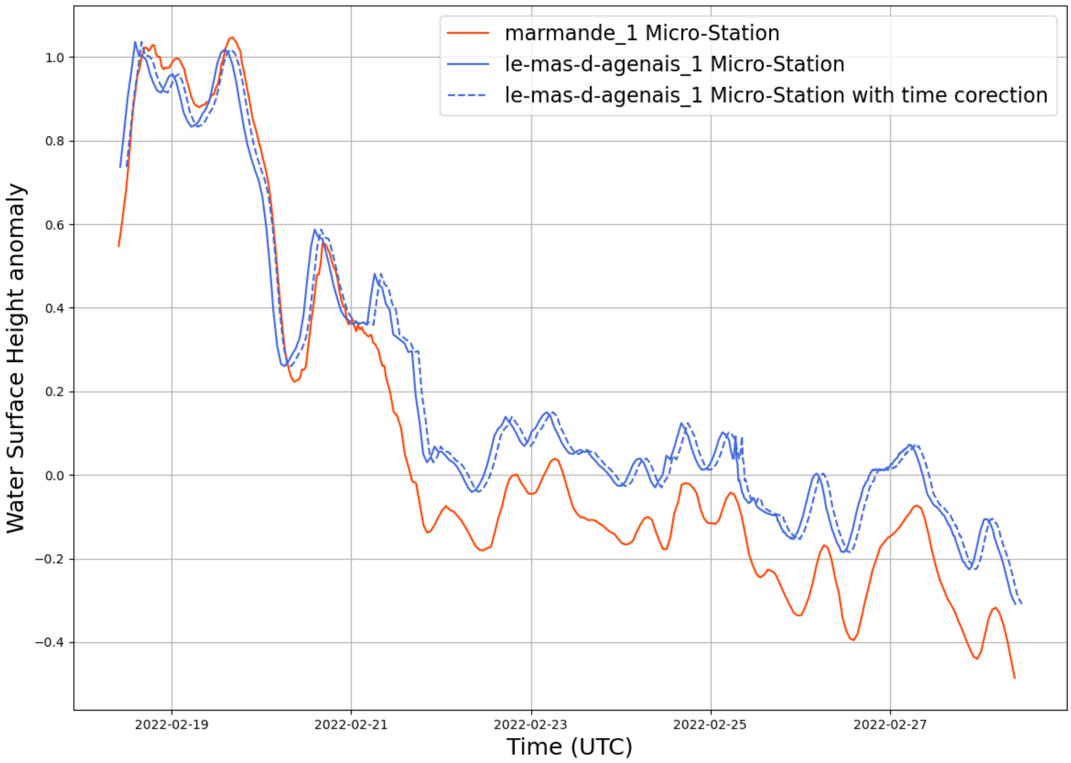


Figure 11: Comparison of WSH anomaly between "le-mas-d-agenais_1" (in blue) and "marmande_1" (in red) over the Garonne river before (solid) and after (dashed) the correction of the propagation time

To summarize, here is the equation corresponding to the FRM measurement:

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

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.

It is important to mention that the ideal FRM scenario would be to use an autonomous drone solution to be able to deploy the drone at the exact time and location of the satellite pass (no matter what time of the day or night). But unfortunately, this solution is not available at this time, and that is the reason why we propose to combine different sensors to provide the best FRM possible.

Finally, the approach we propose here is based on water height interpolation, but we assume to obtain better performances when working with river discharge instead. Of course, this assumption and the associated activities (this method requires bathymetry measurements) can be explored in the future but are not included into the St3TART project.

3.3. Computing FRM over the selected Cal/Val super sites

3.3.1. Canal Du Midi

3.3.1.1. Suitability of the Canal du Midi

The Canal du Midi is a French navigation canal linking Toulouse to the Mediterranean Sea since the 17th century. The Canal du Midi runs for 246 km from Toulouse to the Etang de Thau. The Canal du Midi is a divided canal with one side on the Atlantic side of the watershed, 57 km long, and the other on the Mediterranean side, 189 km long. The Seuil de Naurouze reach is the highest section with an orthometric height of 189 m. The width of the canal at the surface is 16 to 20 metres. The water depth is between 1.8 and 2.5 metres. The Figure 12 illustrates the canal profile from Toulouse (1), to Etang de Thau (8), crossing the Seuil de Naurouze (2), Castelnaudary (3), Carcassonne (4), Trèbes (5), Béziers (6), and Agde (7).

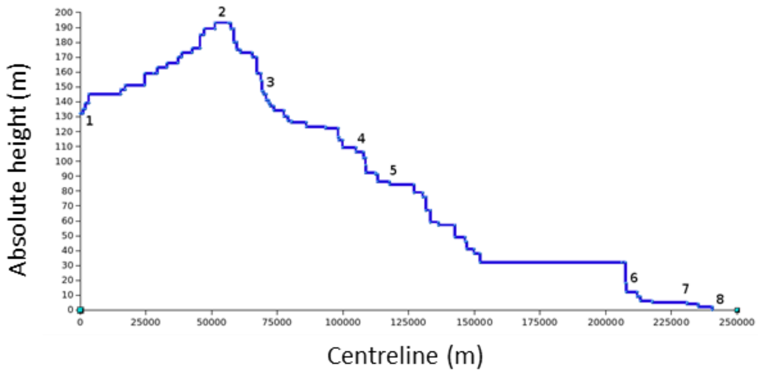


Figure 12: Profile of the Canal du Midi (distances in metres on the curvilinear abscissa from 0 in Toulouse and orthometric heights in metres on the vertical axis).

Figure 13: Map of the Trèbes Cal/Val Super Site with Sentinel-3 tracks represented in solid red lines

The Canal du Midi has been selected as a Cal/Val super site for its characteristics:

- The Canal du Midi has a very simple river topography: it is a flat-water body with a linear slope and a steady controlled water level.
- The Trèbes site has been chosen because of the presence of 2 Sentinel-3A tracks (tracks #16 and #57) on this canal part with a bridge located under the Sentinel-3A reference ground track (under the ground track #16, the bridge is located at less than 100 m)
- Crossing between canal and satellite track is nearly perpendicular.
- There is no other water body near the S3A crossing on the west hand side, while there is the Aude River generating some power returns and thus radargram pollutions on the east hand side (this feature can be interesting to investigate for Sentinel-3 performances)
- A vorteX.io Micro-Station has been installed on this bridge during the project. The site is illustrated on Figure 13

3.3.1.2. Instrumentation installed on the Canal du Midi and associated costs

Following the Cal/Val site classification detailed in part 2.8, this site corresponds to a Complexity Level 0. Thanks to the installation of the instrumentation described in the dedicated Campaign Log: 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.

This exercise has been performed by CLS in the TD-13, we remind here the main result. The FRM is computed as described in part 2.8 and 3.2.2. But as the site is simple (Level 0 class), 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 comparison is performed following the steps described here:

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 (see Figure 14)
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

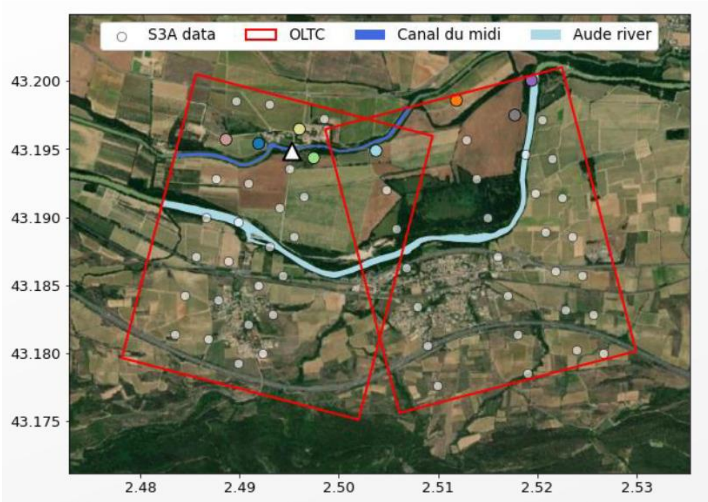


Figure 14: Selection of the Sentinel-3 measurements for comparison to FRM on the Trèbes site

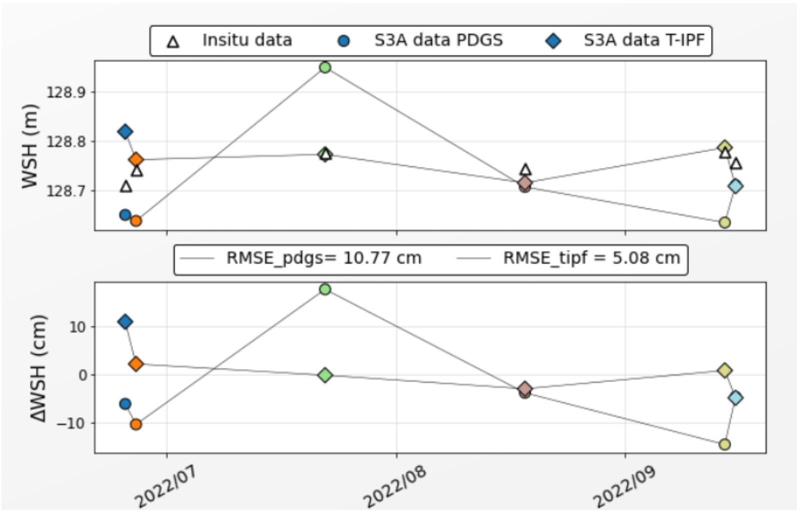


Figure 15: Comparison between FRM and Sentinel-3 measurements on the Trèbes site

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. We also know that there is still room for improvement on the way to process those specular echoes.

The following table provides an estimate of the yearly costs for the Trèbes site over the Canal du Midi.

Description	Unit cost	Quantity	Cost
1 year of vorteX.io micro-station	4800 €/year	1 Micro-Station	4800 €/year
Quality analysis and assessment	Depending on the entity in charge	10 days / year	10 days/year
Total			**4800 €/year + 10 days/year**

Table 2: Estimated cost for the Trèbes site over the Canal du Midi

It is important to note that the micro-station cost is a yearly service cost including all the following features:

- The micro-station and all its equipment (Solar panel, fixing system, etc.)
- The installation of the system (including procedures for obtaining permissions to install, technician costs on the field)
- Data transmission
- Data storage
- Data processing
- Access to a dashboard to visualize and download micro-station measurements in real-time
- API access
- Preventive remote maintenance
- Corrective maintenance (replacement of the micro-station or the solar panel in case of failure, vandalism, etc.)

3.3.1.3. Conclusion on the Canal du Midi

Following the results detailed in the TD-13 (FRM Campaign Final Report for Inland Water) [RD28], this site provides excellent results and allows to estimate the performances of Sentinel-3A on an ideal case. It leads to a RMSE between the current Sentinel-3A L2 products and the FRM measurement of 10.77 cm and a RMSE of 5.08 cm with the new Sentinel-3A Thematic hydro products. This site should be maintained in the future to meet the long-term requirement of the MPC.

3.3.2. The Garonne River

3.3.2.1. Suitability of the Garonne River

The Garonne River is located in Southwest France and drains an area of 56,000 km square. Its mean annual discharge near its outlet, at Tonneins where the river width is about 200 m, is around 600 m3 s-1. At global scale, according to the Global Runoff Data Center (GRDC) discharge database, it is the 120th largest river in the world by its annual discharge and the 3rd in mainland France. It is therefore a medium river according to Meybeck et al. (1996) [RD9], and a river which is representative of medium river cases. The Garonne River has a pluvio-nival regime, with a low flow period between July and October and high flow period between December and April. The Garonne supports an agricultural activity that uses 70% of the total water uptake (mainly from surface water) during low flow period (Sauquet et al., 2009 [RD10]; Martin et al., 2016 [RD11]). The actual water height variation over a typical year is several metres. The daily variation during floods can be as large as 2 metres.

Water level and discharge gauges on most rivers in France are operated by regional public agencies (DREAL – Directions Régionales de l'Environnement, de l'Aménagement et du Logement) and their measurements are collected by the Service Central de l'Hydrométéorologie et d'Appui à la Prévision des Inondations (SCHAPI) within the national "Banque Hydro" database (http://www.hydro.eaufrance.fr). Four gauges from this database (Verdun-sur-Garonne, Lamagistère, Tonneins and Marmande), are available on this River and have been used in the past for relative comparison with altimeter data. The river width is around 130 m at Verdun-sur-Garonne, 150 m at Lamagistère and 200 m at Tonneins and Marmande. A precision of the order of 20-50 centimetres has been demonstrated using Jason-2, ENVISAT and SARAL missions. Most limitations were related to the actual performances of the current retracking solutions used, but the author also mentioned the impact of the heterogeneity of the scene observed by the altimeter (a canal is observed very close to the riverbed, there is some sand banks on the river depending on the river height…) and the distance between the altimetry virtual station and the gage. It is important to mention that the Hydroweb and Dahiti databases (among others) provide information, not on the actual altimeter data location, but on the theoretical ground track position. Thus, they do not consider the actual cross track distance evolution that occurs during the mission lifetime. Even if the ground track is maintained to +/- 1 km from the nominal ground track, this quite small distance difference can have a large impact when analysing the water surface height provided by the altimeter and/or when comparing the altimeter WSH values with in-situ measurements (river slope is in the order of 60 cm/km in this area).

The selected Cal/Val super site on the Garonne River is located between Le Mas d'Agenais and Marmande where 2 Sentinel-3A tracks cross the Garonne River in 4 locations and with different crossing angles. A Sentinel-6 track is also present in the area, crossing the river in 3 locations and also quite parallel to the river. Figure 16 shows a map of the area with Sentinel-3A reference ground tracks represented by bold red lines, the +/-1 km area around the reference ground track is represented by 2 thin red lines on either side of the reference ground track and the Sentinel-6 reference ground track is represented by the yellow line. It is also important to mention that this site is located within the swath of the SWOT Cal/Val orbit (1-day orbit). Figure 17 illustrates the location of the existing sensor from the French national network (Vigicrues station) and the 5 Sentinel-3A virtual stations. In addition, Figure 18 represents the actual locations of Sentinel-3A measurements at P0, P1 and P2. This map clearly shows the excursion of the actual Sentinel-3A measurements along the river due to the current constraints of the orbit control.

P0 is a cross point between Sentinel-6 and Sentinel-3A over the river with a nearly perpendicular approach; a canal is also present nearby. P1 is a Sentinel-3A observation only, the Garonne being nearly parallel to the ground track on the east side, the viewing angle being close to 45° at the theoretical ground track position. P2 is also a Sentinel-3A observation only, the Garonne being nearly perpendicular to the ground track. P3 is observed by Sentinel-3 but on a different track and finally P4 is observed by Sentinel-6 very close to a bridge location.

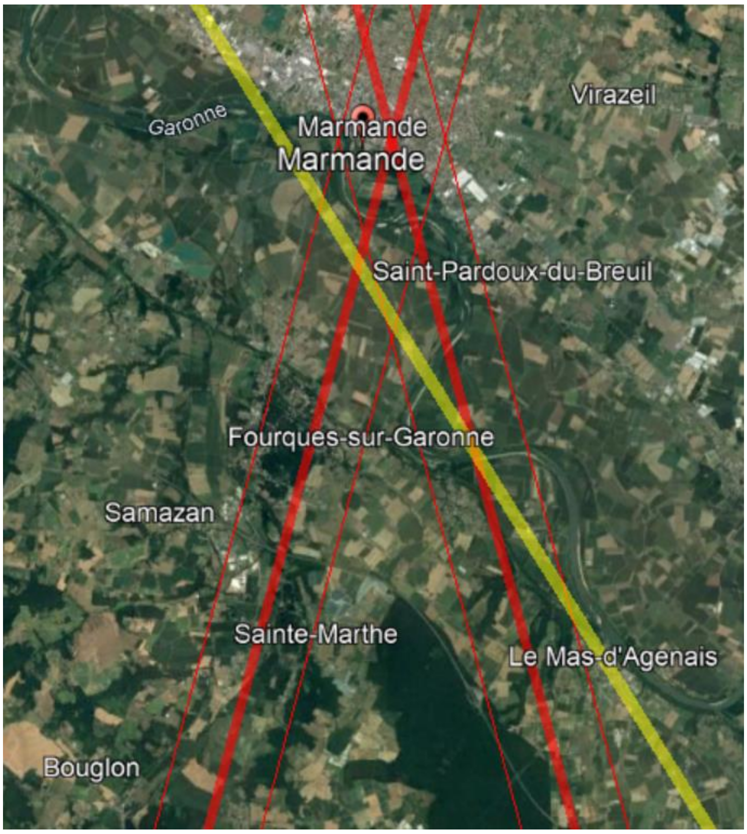


Figure 16: Map of the Cal/Val super site on the Garonne River near Marmande. Bold red lines: Sentinel-3A reference ground tracks. Thin red lines: border of the +/-1km area around the Sentinel-3A ground tracks. Yellow line: Sentinel-6 reference ground track

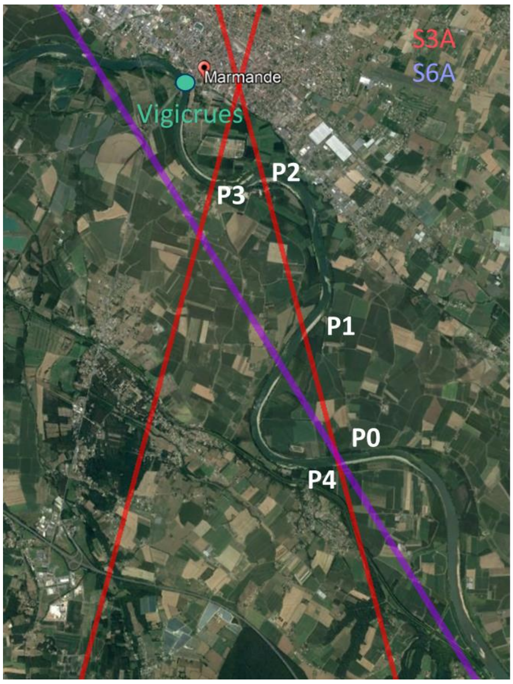


Figure 17: Location of the Vigicrues station (French national network) on the Marmande Cal/Val super site and locations of the different Sentinel-3A virtual stations (P1-P4)

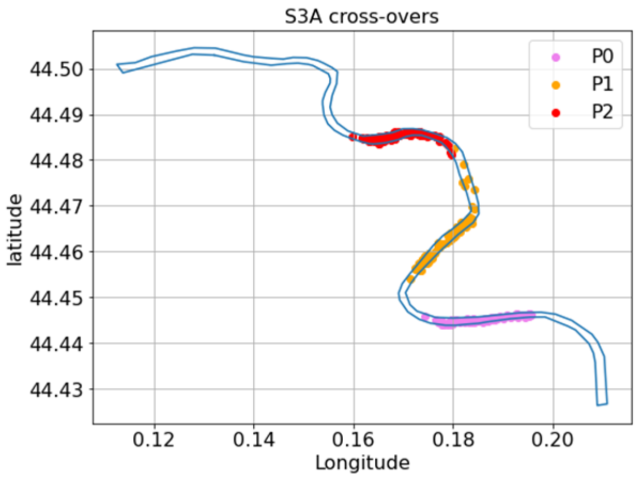


Figure 18: Actual locations of Sentinel-3A measurements at P0, P1 and P2.

During the St3TART hydrology workshop held in December 2021, François Boy presented Cal/Val analysis of Sentinel-3A measurement in this area using the Vigicrues station located in Marmande. He showed that the further away the measurements are from the in-situ station, the greater the differences, up to several metres. He demonstrated that this effect is due to the river topography based on a drone campaign performed in 2018, providing the water topography along the river (the water surface height profile along the river). The use of this information as a correction to the Sentinel-3A measurements allows to drastically improve the adequacy between satellite and in-situ measurements as shown in Figure 20.

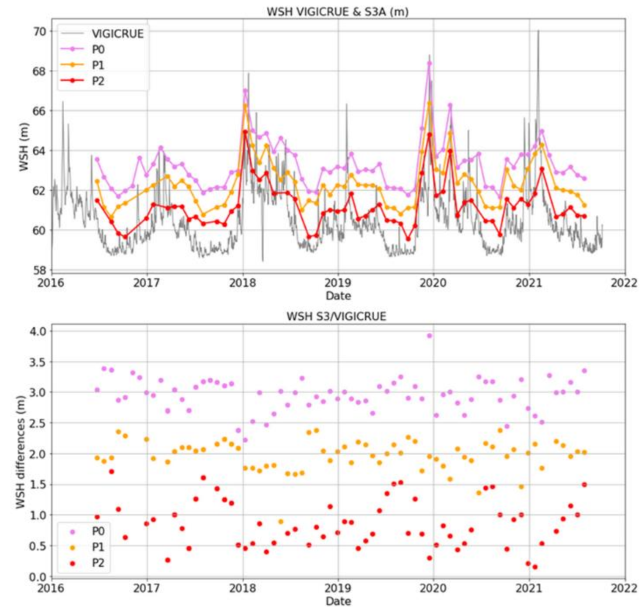


Figure 19: Comparison of Sentinel-3A water surface height measured at P0 (purple), P1 (yellow) and P2 (red) and Vigicrues measurement from the Marmande station (grey line) on the top figure. Plot of the difference between Vigicrues WSH and Sentinel-3A WSH on the bottom figure.

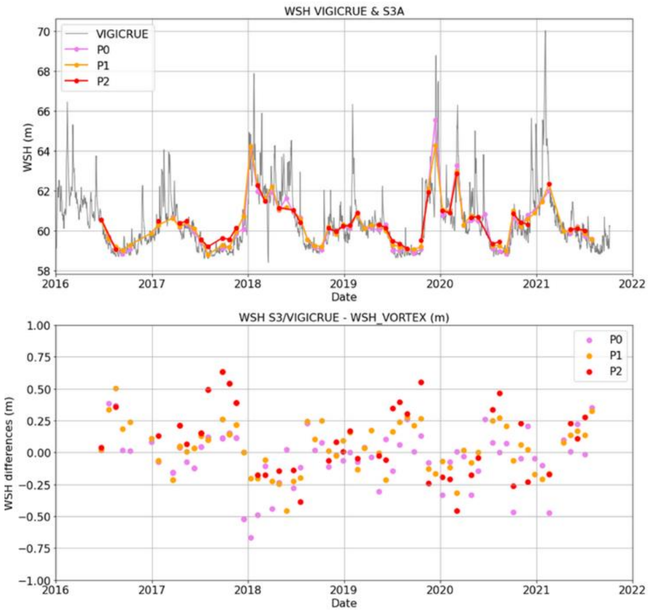


Figure 20: Comparison of the corrected Sentinel-3A water surface height measured at P0 (purple), P1 (yellow) and P2 (red) and Vigicrues measurement from the Marmande station (grey line) on the top figure. Plot of the difference between Vigicrues WSH and Sentinel-3A WSH on the bottom figure.

All these characteristics make this area a Cal/Val site of great interest eligible for super site status.

3.3.2.2. Instrumentation installed on the Garonne River and associated costs

On the Marmande site over the Garonne River, we have installed in the framework of the St3TART project 3 Micro-Stations (marmande_1, marmande_2 and le-mas-d-agenais_1) as illustrated on the map in Figure 21, performed 2 drone campaigns funded by CNES (a third one will be performed in early 2023 at high water level) and installed 5 pressure sensors. Several field trips were performed on site to identify potential new sites where additional pressure sensors could be installed. This will be done in the framework of the SWOT Cal/Val project and St3TART will in the future benefit from this dense network.

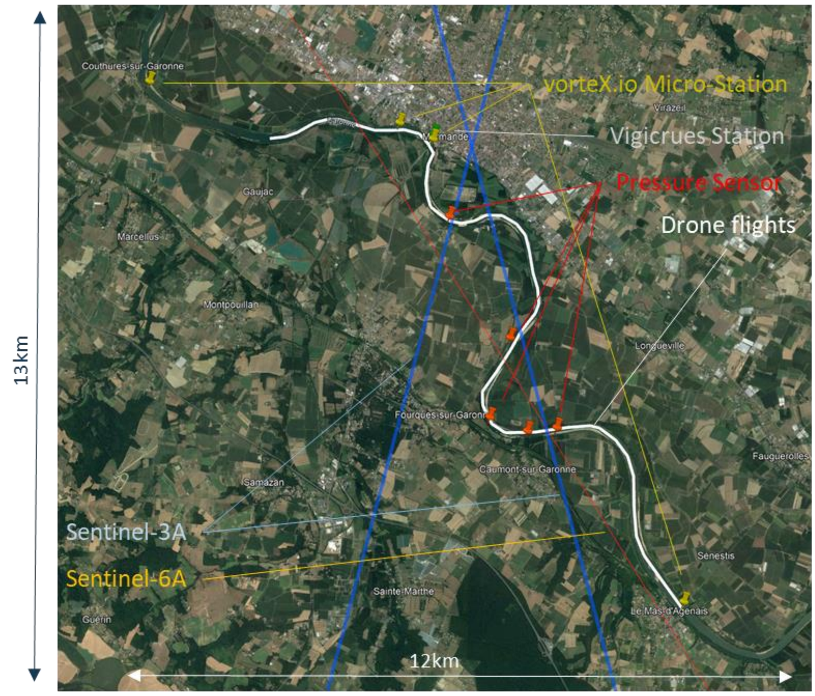


Figure 21: Map of the Marmande Cal/Val super site with all the instrumentation installed

Following the Cal/Val site classification, detailed in section 2.8, this site corresponds to a Complexity Level 3. The Micro-Stations are not installed just under the Sentinel-3A ground tracks. The slope must be accounted for to correct the in-situ measurement from the river topography. The topography is complex, and the slope depends on the water height. The Garonne River is also a very dynamic waterbody, the in-situ sensor must perform its measurement by taking account of the propagation time with the virtual station. Thanks to the installation of the instrumentation described in the dedicated Campaign Log (3 vorteX.io Micro-Stations and 2 drone campaigns), the computation of FRM values is done in an operational way following the strategy described in chapter 3.2 (as mentioned above, a mock-up is available in a Jupyter Notebook format on an online and open access GitHub and an ATBD will be provided to users).

The following table provides an estimate of the yearly costs for the Garonne River including 1 year of 3 vortex.io Micro-station and 3 drone deployments. Of course, the 3 drone deployments are not mandatory each year.

Description	Unit cost	Quantity	Cost
1 year of 3 vorteX.io micro-stations	4800 €/year	3 Micro-Stations	14400 € / year
1 drone campaign with data processing	15 k€	3	45 k€
Quality analysis and assessment	Depending on the entity in charge	20 days / year	20 days /year
Total			**59.4 k€ /year + 20 days / year**

Table 3: Estimated cost for the Marmande site over the Garonne River

3.3.2.3. Conclusion on the Garonne River

Following the results detailed in the TD-13 [RD28] the Marmande site over the Garonne River represents a very interesting site as it has been identified as the highest complexity level: 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 value added 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 4 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 this document to provide valuable FRM even in the case of high complexity sites. This site should be maintained in the future to meet the long-term requirement of the MPC.

3.3.3. The Maroni River

3.3.3.1. Suitability of the Maroni River

The Maroni River is located in French Guyana, South America. Its basin is larger than 65 000 km², and its mean discharge at Saint Laurent du Maroni (near the mouth) is around 1 700 m3/s. Maroni River is the largest tropical river of Europe and the only one monitored in the framework of St3TART. Its flow variations are quite fast, with potentially several metres of water level variation in a few days. While the Maroni River basin is quite well equipped in monitoring devices on the French side, the inflow from Surinam (which accounts for more or less 50 % in terms of discharge) is unknown. This makes any monitoring of the river for navigation uneasy, whereas it is the only path toward upstream villages for people and goods.

The location of the Cal/Val sites (site 1 and site 2) selected for the Maroni River basin are shown in Figure 22. Among the several crossings between a major river and Sentinel-3 ground tracks, we identified two potential sites of interest: the first one, on the downstream part of the Maroni, is a crossover between Sentinel-3A and Sentinel-3B tracks. It is located near the city of Apatou and the river is almost 1 km wide at this location. The second one is located on the Tapanahoni River, the Surinam tributary of the Maroni. The river is 400 m wide at Kio Kondé.

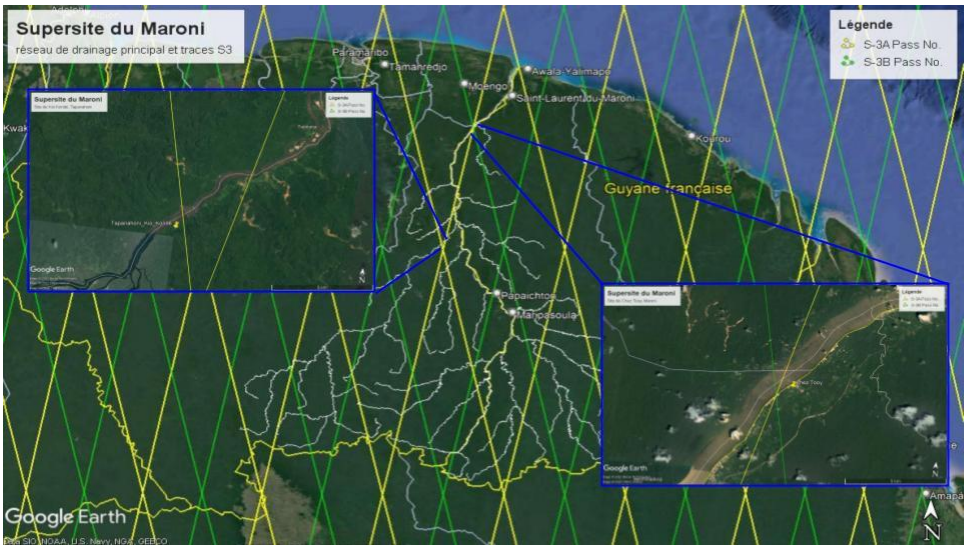


Figure 22: Location of the Maroni River basin and its main rivers (in white). The two boxes show the location of site 1 (right) and site 2 (left) together with the Sentinel3 ground tracks (S3A in yellow, S3B in green).

Both sites 1 and 2 are very interesting in terms of altimetry Cal/Val and for defining a roadmap toward a FRM for altimetry. In site 1, the proximity of a city and the easy accessibility ensures a large amount of data to be analysed (ongoing work), while site 2 should provide an insight of the impact of across-track slope variability on the quality of the time series and possible recommendations on data comparisons and processing. For the aforementioned reasons, the Maroni site is suitable to be a Cal/Val super site.

3.3.3.2. Instrumentation installed on the Maroni Cal/Val super site and associated costs

Site 1: During the 2021 flood, the pier where site 1 sensor had been installed was swapped away. A new stronger pier was constructed, and a pressure sensor installed. An OECS gauge was also installed on the same structure and will allow the comparison between citizen data and staff gages. Flow GPS profiles around this site were collected (under processing) and will provide the water surface slope that will consolidate the comparison between in-situ and Sentinel-3A&3B data. The GPS slope will be also compared with ICESat-2 data.

Figure 23: site 1. Showing the wharf built to support the instruments, namely a pressure sensor (in the pipe fixed to the last but one pilar), a rule (fixed to the pipe and the pilar), and the floating GNSS device (antenna being at a fixed height on the tripod) used (when trailed by a canoe) to measure the absolute level and slope of the water surface and to check for the stability of the pressure sensor (when motionless beside the wharf as it is in the picture)

Description	Unit cost	Quantity	Cost
Wharf	8 k€	1	8 k€
Pressure sensor with pipe and accessories	1.5 k€	1	1.5 k€
Rule	0.5 k€	1	0.5 k€
1 GNSS carpet campaign	30 k€	1	30 k€
Maintenance visit	1 k€	3 (1 every 4 months)	3 k€/year
Quality analysis and assessment	Depending on the entity in charge	10 days / year	10 days / year
Total			**10 k€ + 33 k€ / year + 10 days / year**

Table 4: Estimated cost for the site 1 over the Maroni River

Site 2: A stream gage was installed at site 2 (Kio Kondé) in Suriname. This location is particularly interesting because there is a Sentinel-3A crossover, and because the reference ground track passes just upstream a break. As a consequence, the departure of the satellite from its reference ground track (and the oscillations of this departure) will have a great impact on the quality of the satellite altimetry time series delivered. As an illustration, the position of the actual pass in time is shown Figure 24.

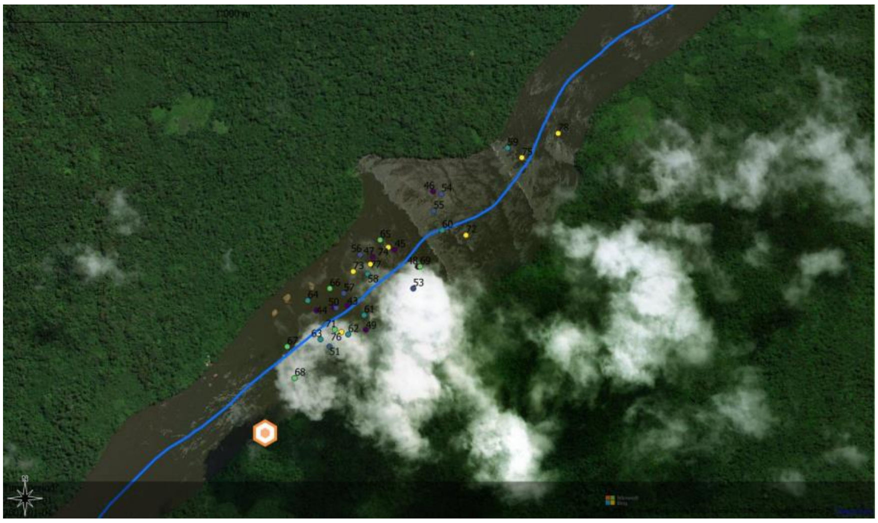


Figure 24: Location of the actual pass along the stream and over time (the colour code indicates the cycle) at Kio Kondé (Tapanahoni, Suriname).

Figure 25: site 2: installation of the gauge at Kio Konde, Tapanahoni river in Suriname

No instrument cost, gauge was paid by local partner, absolute levelling is based on the GNSS carpet shown in Figure 23.

Maintenance cost: participation to the costs of each cruise (every 6 months) to visit the site :1 k€.

Description	Unit cost	Quantity	Cost
Maintenance visit	1 k€	2 (1 every 6 months)	2 k€/year
Additional pressure sensor + connectivity system	2.5 k€	1	2.5 k€
Quality analysis and assessment	Depending on the entity in charge	10 days / year	10 days /year
Total			**2.5 k€ + 2 k€ / year + 10 days / year**

Table 5: Estimated cost for the site 2 over the Maroni River

3.3.3.3. Conclusion on the Maroni River

The results detailed in TD-13 [RD28] demonstrate the value of the site with a RSME of 42 cm on the first site between the standard Sentinel-3 L2 product and the FRM. Reprocessing the site with a physical retracker leads to a RSME of 30.2 cm and a bias of 5 cm. This site is impacted by tidal effects. If the average bias is removed, the RMSE decreases to 22.6 cm.

On the second site, the computed RMSE is about 55.6 cm and the bias of 63.8 cm with the standard L2 products. With the physical retracker the RMSE is decreased to 34.7 cm and a bias of 68.8 cm. The local slope variation, and its impact on varying pass location of the satellite turns 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.

3.3.4. The Rhine River (French part)

3.3.4.1. Suitability of the Rhine River (French Part)

The Rhine is the European river par excellence. The river flows through Switzerland, Austria, Germany and the Netherlands. It serves as Switzerland's border with Liechtenstein, Austria and Germany, and it marks the border between Germany and France. The Rhine River is the longest Western European River, 1325 km, draining the third largest European watershed with 185 000 km^2.

In the transborder Rhine context, the organisation and geographical distribution of the gauge networks is particularly complex, associating local (Eurométrople Strasbourg, Ville de Mulhouse…), regional (LUBW, CG 68-CEA) and national institutes (Vigicrues-SCHAPI, DREAL, VNF, EDF, BfG, NSW), both in Germany and France, but also from Switzerland (CHR).

The St3TART work has been focused on the Superior Rhine, though including a small portion of the inferior Rhine. The Superior Rhine part begins at Basel and flows about 300 km to the north, through the Rhine Graben, dropping from 252 m to 75 m in altitude. It is joined by the Ill River near Strasbourg, the Neckar at Mannheim and the Main near Mainz. The southern half of the Upper Rhine forms the border between Germany and France. The lower half in the north separates Rhineland-Palatinate in the west from Baden-Württemberg and Hesse in the East.

One particularity of the Superior Rhine is that between 1817 and 1876, the Upper Rhine underwent extensive straightening and construction work, which restricted its overflow and made it navigable from 1907. From the Kembs dam, to the Iffezheim one (the last on the river), the Rhine is now a canal, named “Canal d’Alsace”, with 12 successive dams-locks, each having a fall height of about 12-14 m, dropping from 244 to 111 m. In addition to the canalised Rhine, the Old Rhine flows in parallel segments. Often starting at the foot of a dam of less than ten metres in height, the connection to the slope is made either naturally or via small weirs. The river width is around 130 m when the Old and Canal Rhine are flowing in parallel, up to 330m in large sectors when there is only the Rhine Canal.

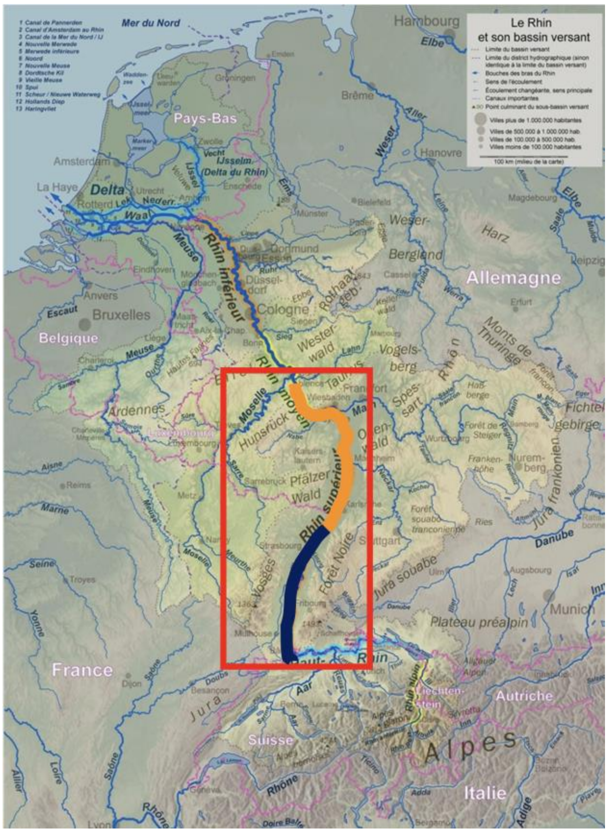


Figure 26: Map of the parts of the Rhine that will be covered in the St3TART project

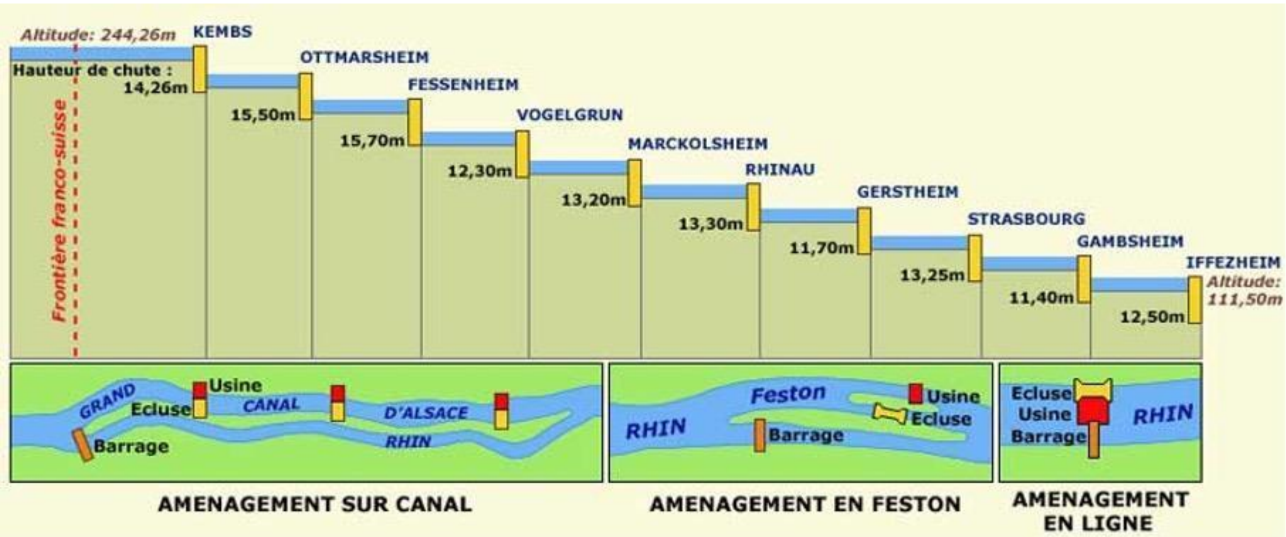


Figure 27: Scheme of the Rhine dam successions with fall heights as well as the different parallel structures that can be observed on the Old Rhine

Over rivers and lakes in the Rhine basin, there are about 96 virtual stations for Sentinel-3A and about 103 virtual stations for Sentinel-3B (Figure 28).

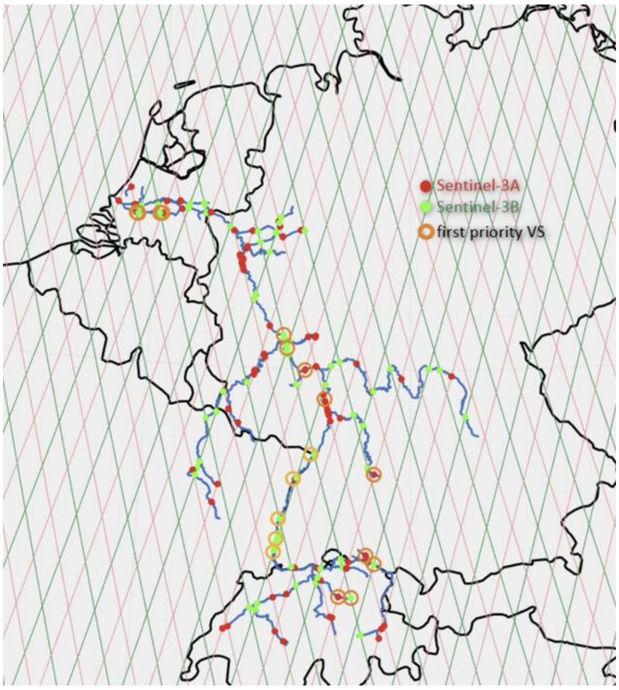


Figure 28: Rhine River with Sentinel-3A and 3B ground track, 199 virtual stations and 10 selected water bodies for analysis and validation

One is particularly interesting as it corresponds to two tracks crossing the Rhine with a distance of 2000 m, and in the vicinity of a gauge station, upstream of the Gambsheim Dam (France) knowing that the slope of the Rhine Canal is about 1 to 1,5 cm/km (Figure 29).

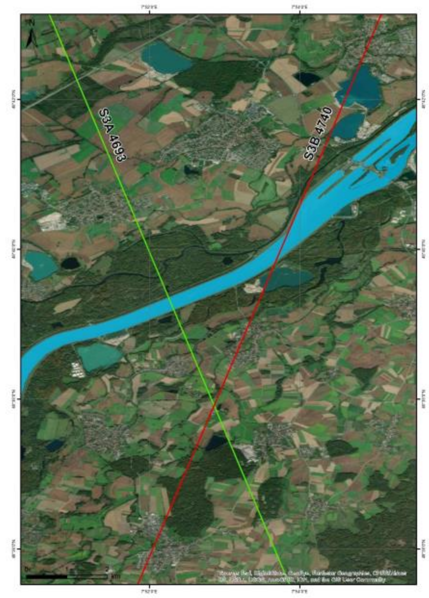


Figure 29: Sentinel-3A and -3B ground tracks, orbit 4693 and 4740 respectively, crossing over the Rhine Canal, at a distance of 2000 m upstream of the Gambsheim dam (France), knowing that the slope of the Rhine Canal is about 1 to 1.5 cm/km

3.3.4.2. Instrumentation installed on the Rhine River (French part) Cal/Val super site and associated costs

On the French part of the Rhine River, we have identified 4 super sites. On the 3 first sites (“Ottmarsheim”, “Gerstheim”, “Strasbourg”) we have installed the station just under the satellite ground track. These are complexity level 0 sites. The Rhine River is along the Sentinel-3 ground track. With a slope measurement we can provide FRM measurements at the location of other virtual stations all along the Rhine River. With the slope measurement these sites are also labelled complexity level 1 or 2 depending on the dynamic of the Rhine River. On “Ottmarsheim” the dynamic of the Rhine River is strong with daily oscillations on the canalised part. On this site the time lag between the virtual stations and the in-situ sensor must be accounted for. This is a complexity level 2 site. On the 2 other super sites the Rhine River dynamic is very slow, the time lag is not necessary. These are complexity level 1 sites. On the last site ("Gambsheim") the in-situ sensor is not located under the satellite ground track. The slope must be accounted for but the dynamic is negligible, so it is a complexity level 1 site.

On the Rhine River, we have installed in the framework of the St3TART project 6 Micro-Stations, 4 in the vicinity of Strasbourg (strasbourg_1, erstein_1, erstein_2, gesrtheim_1) and 2 in the southern part, near Ottmarsheim (chalampé_1, ottmarsheim_1). Over the Rhine canalized part, i.e. Grand canal d'Alsace, upstream and downstream of the Gambsheim dam, a flight cumulating 8 km was done in September 2022 (Figure 30), the following day, 11 km of acquisitions were carried out over the upstream and downstream of the Grand canal as well as over Old Rhine ion the Ottmarsheim area (Figure 31).

Figure 30: UAV flight in the vicinity of the Gambsheim dam performed in mid-September 2022

Figure 31: UAV light in the vicinity of the Ottmarsheim site on the 13-09-2022, due to hard field conditions, the extent of the flight over the Old Rhine is shorter than scheduled

The UAV flight up to the Chalampé_1 Vortex station located over the Grand Canal d'Alsace, of course drone and micro-station measurements were compared (Figure 32), indicating a very good agreement.

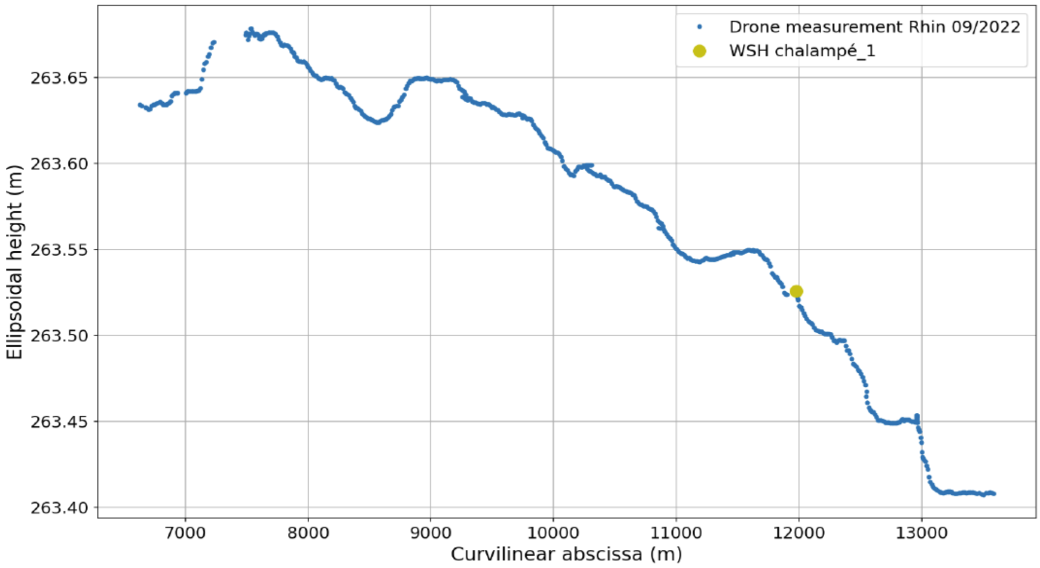


Figure 32: Comparison between drone measurements and micro stations chalampé_1

The following table provides an estimate of the yearly costs for the French part of the Rhine River including 1 year of 6 vortex.io Micro-station and 3 drone deployments. Of course, the 3 drone deployments are not mandatory each year.

Description	Unit cost	Quantity	Cost
1 year of 3 vorteX.io Micro-Stations	4800 €/year	6 Micro-Stations	28 800 €/ year
1 drone campaign over the Rhine River with data processing	20 k€	1	20 k€
Quality analysis and assessment	Depending on the entity in charge	25 days / year	25 days / year
Total			**48.8 k€ / year + 25 days / year**

Table 6: Estimated cost for the French part of the Rhine River

3.3.4.3. Conclusion on the Rhine River (French Part)

The detailed results are provided in TD-13 [RD28].

The Rhine River is a very interesting site because of the river configuration. Indeed, 2 branches of the Rhine River 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 this document allows to provide good FRM with small 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.

3.3.5. The Rhine River (German part)

3.3.5.1. Suitability of the Rhine River (German Part)

After the Iffezheim dam, the Rhine flows naturally and this up to Coblenz. The last section, from Rüdesheim am Rhein to Coblenz (the so-called Middle Rhine) is particularly famous for its gorges' sector. At Coblenz, two major tributaries, the Moselle and Lahn rivers, are connected with the Rhine. On its free course, from Iffezheim to Coblenz, the Rhine width is around 320 m. In this part, the flow is controlled, refocused towards the main bed to guarantee navigation even during low water periods, and to control sedimentation. For this purpose, a groyne system has been erected in many places. During periods of high water, the presence of these hydraulic structures generates interference (ripples) in front of these structures, which create a regular pattern of smooth and rough water surfaces.

Figure 33: Groyne system on the shore of the free Rhine part

Figure 34: Alternance of calm and rough water surfaces due to the presence of the groyne system

Over rivers and lakes in the Rhine basin, there are in total about 96 virtual stations for Sentinel-3A and 103 for Sentinel-3B. Among these virtual stations, 4 water bodies are selected as Cal/Val “super sites”, which provide a combination of different geometric and geomorphological characteristics (see Table 7). For the selected super sites, efforts were made to obtain permission to install micro-stations and also to acquire in-situ data from local authorities and publicly available databases.

			S3A			S3B			
	Object	Country	Track	crossing ang.	coordinates	Track	crossing ang.	coordinates	Neighboring topography
1	Mannheim	Germany	313	ca. 0	49.6397° 8.3825°				flat topography
2	Oestrich-Winkel	Germany	358	ca. 45	49.9876° 7.9993°				relatively flat
3	Esslingen	Germany	586	ca. 90	48.7271° 9.3236°				hilly
4	Sankt Sebastian	Germany				313	ca.20	50.4097° 7.5738°	relatively flat

Table 7: List of Cal/Val sites on the German part of the Rhine River

As an example, Figure 35 shows a selected super site along the Sentinel-3A in Mannheim, which runs almost parallel to the Rhine River for about 40 km. Four micro-stations will be installed at this super-site, which together with three in-situ stations will constitute an ideal Cal/Val site. Among the four micro-stations, two are already installed and the remaining are planned for the near future. The available in-situ data are in Speyer, Mannheim and Worms, whose data are available from March 2016 until April 2022.

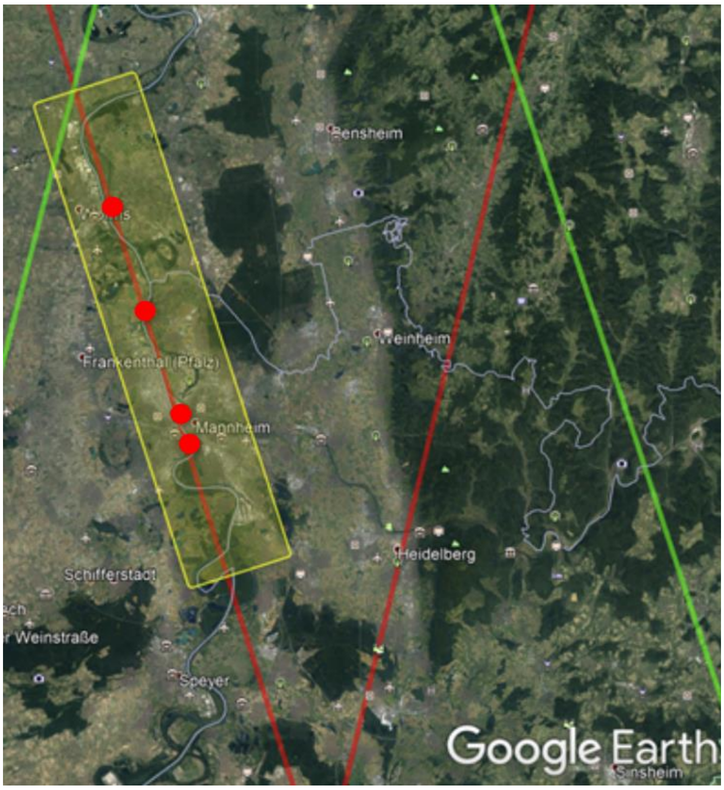


Figure 35: Crossing track 313 of S3A over the Rhine River close to Mannheim for about 37 km. Red dots represent the location of micro-stations

Figure 36 shows the water level time series of S3A in a satellite ground track very close to Worms together with water level time series of the three in-situ levels without slope correction, correlating highly with each other. The offset in the time series from Speyer to Worms emphasizes the need for the slope correction when using in-situ gauges of further distances (described in 3.2.2). The legend entry for the dashed altimetric time-series is an abbreviation by GIS for the used retracker and applied geophysical corrections.

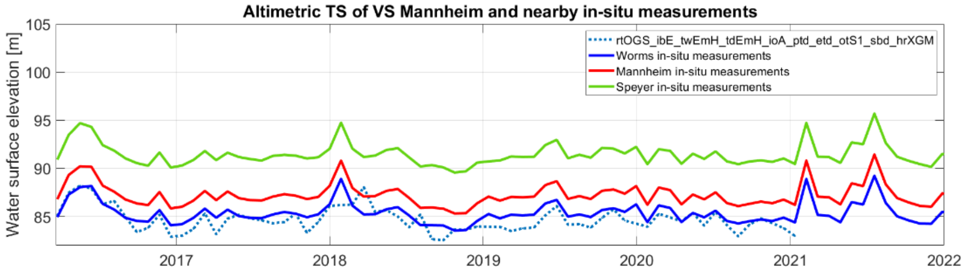


Figure 36: Water level time series of S3A in a satellite ground track very close to Worms together with water level time series of the three in-situ levels without slope correction

3.3.5.2. Instrumentation installed on the Rhine River (German Part) Cal/Val super site and associated costs

Over the German part of the Rhine River, 4 sites have been selected as Cal/Val super sites where Micro-Stations are and will be installed:

- Esslingen am Neckar
- Mannheim (4)
- Oestrich-Winkel
- Sankt Sebastian

The map of Cal/Val super sites over the Rhine River for the German part is shown in Figure 37. As of now, micro-stations were successfully installed in Oestrich-Winkel, Mannheim (two of four) and Esslingen am Neckar (see figure below). The installations of the final two in Mannheim and Sankt Sebastian are soon to be arranged. These will be executed on German highway bridges (Autobahn) and hence required more time to obtain permissions. Due to the 40 km long study area, the Mannheim Cal/Val super site is open to other installation possibilities and will therefore continue to be equipped in the near future. In addition, another micro-station in Esslingen is being discussed due to the complexity of the site.

Figure 37: Map of the selected Cal/Val super sites on the Rhine River for the German part

Figure: Images of the installed micro-stations in Esslingen am Neckar (left), Oestrich-Winkel (top right) and Mannheim (bottom right)

Among the selected sites, Esslingen is the only site with a Complexity Level of 1. All the other sites have a Complexity Level of 0 as shown in Figure 38 and according to the classification detailed in chapter 2.8. In this context, no slope measurement is required except for Esslingen. However, the location "Esslingen am Neckar" is only defined as a Cal/Val super site of Complexity Level 1 due to the considerable distance between the installed micro-station and the nominal ground-track of Sentinel-3A.

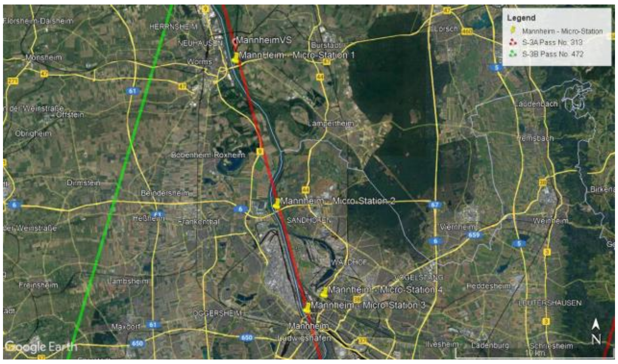


Figure 38: Detailed map of the Micro-Station installation over the German part of the Rhine River. Top left: Esslingen, top right: Mannheim, bottom left: Oestrich-Winkel, bottom right: Sankt Sebastian.

On the “Esslingen am Neckar” super site, the Micro-Station is not installed right beneath 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. The investigations described in the latest release of TD-13 conclude that no slope shall be accounted for. Hereby, the fixed ellipsoidal heights of two local gauges are compared to each other. A property of the site that must be closely analysed in the future is the division of the river through canalization. The Northern branch of the Neckar is a low-water section whereas the Southern branch yields higher water surface elevation. The observations from the micro-station will be comparable to those altimetric measurements over the high-water section of the Neckar. For altimetric measurements over the lower section of the river, in-situ gauges at the lock and weir will have to be taken for validation. In the future, a second micro-station installed on a pedestrian bridge over the Northern branch, could facilitate the validation of measurements occurring over the low-water section of the Neckar. The distance between the Micro-Station and the virtual station is considerable, but the waterbody is not very dynamic, so there is no propagation time to be accounted for. With all these parameters, we can conclude that this site remains a complexity level 1.

The following table details the costs associated to the Cal/Val super site of the German part of the Rhine River.

Description	Unit cost	Quantity	Cost
1 year of 5 vorteX.io Micro-Stations	4800 €/year	5 Micro-Stations	24 k€/year
Quality analysis and assessment	Depending on the entity in charge	25 days / year	25 days / year
Total			**24 k€ / year + 25 days / year**

Table 8: Estimated cost for the German part of the Rhine River

3.3.5.3. Conclusion on the Rhine River (German part)

In the TD13 document [RD28], 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 as 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 the 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 TD-13 [RD28], 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 were planned at the beginning of the project and can be installed now (permissions granted).

3.3.6. The Po River

3.3.6.1. Suitability of the Po River

The Po River is located in Northern Italy and drains an area of 74,000 km2. It is the longest and largest Italian river, with a mean annual discharge of around 1490 m3s-1 at the Pontelagoscuro station (91 km from the mouth) near Ferrara. It flows in East-West direction in a single branch of 652 km-long through one of the most important economical regions of the country and the largest alluvial plain to which it gives its name, the Po Valley. This is one of the largest contiguous agricultural areas of Europe and more than 30% of water is extracted from surface water for agricultural purposes. Climatic and hydrological regimes vary from the glacial and nival type in the Alps and Apennines to the pluvial yet drier regime in the flat region. The Po River is selected due to its richness of hydrometric data availability (more than 20 stations along its course from Turin to Ferrara).

Considering its geometrical characteristics and the amount of available hydrological observations, the Po River represents an ideal test case for the validation of altimetry satellite missions. Comparing the water levels derived by radar altimetry satellite against the in-situ stations of Sermide and Pontelagoscuro, Tarpanelli et al. (2013) [RD18] found RMSE of 0.87 and 0.75 for ERS-2 and 0.59 and 0.61 for ENVISAT. Schneider et al. (2018) [RD21] analysed the water levels over 12 in situ stations from Carignano to Polesella and compare them with the Cryosat-2 observations obtaining on average RMSE of about 0.34, 0.40 and 0.37 respectively for the three acquisition modes (LRM, SAR and SARIn). Tarpanelli et al. (2019) [RD20] analysing the anomalies of the Sentinel-3A time series with respect to those of six in situ stations (from Pontebecca to Pontelagoscuro) found coefficient of determination greater than 0.93 and Nash-Sutcliffe greater than 0.8. Other examples in literature demonstrated the utility of altimetry observations along the Po for the calibration of the hydraulic model parameters (Domeneghetti et al., 2014 [RD22]; Domeneghetti et al., 2021 [RD23]) and for the river discharge estimation (Tarpanelli et al., 2015 [RD19]; Tarpanelli et al.,2019 [RD20]).

Four Cal/Val “super sites” have been selected along the Po River and they are located at Casale Monferrato, Boretto, Isola Pescaroli and Pontelagoscuro. Figure 39 illustrates the locations of the existing sensors from the regional networks, the satellite tracks, and the selected super sites. It is worth mentioning that the super sites are also equipped with stations from vorteX.io.

Drone campaigns have been performed during the St3TART project to determine the slope and the river topography for a correct evaluation of the satellite measurements.

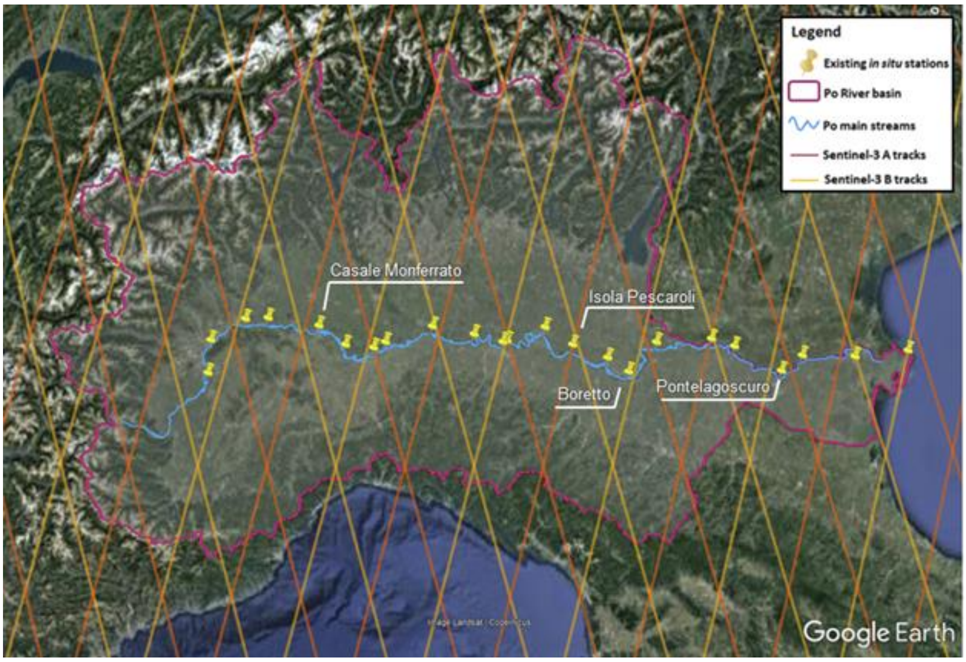


Figure 39: Location of the in-situ stations of the regional networks and the super sites along with the location of the Sentinel-3 A and B tracks

3.3.6.2. Instrumentation installed on the Po River and associated costs

4 stations have been installed on the Po River: Casale Monferrato, Isola Pescaroli, Boretto and Pontelagoscuro. The detailed maps of the 4 sites are presented in Figure 40. In Casale Monferrato, Isola Pescaroli and Pontelagoscuro, Sentinel-3A and sentinel-3B ground tracks are present. In Boretto, there is only a Sentinel-3A ground track. As mentioned above, 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 chapter2.8, the Isola Pescaroli site corresponds to a complexity level 0 site for Sentinel-3B and corresponds 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.

Figure 40: Detailed map of the instrumentation over the Po River. Top left: Casale Monferrato, top right: Isola Pescaroli, bottom left: Boretto, bottom right: Pontelagoscuro

A micro-station has been installed on each site following the maps of Figure 40. In addition, a drone flight has been performed on each site (flight plan represented by the white line) to provide the slope information between the satellite ground track and the in-situ Micro-Station.

Description	Unit cost	Quantity	Cost
1 year of 4 vorteX.io Micro-Stations	4800 €/year	4 Micro-Stations	19 200 €/year
1 drone campaigns with data processing	28 k€	1	28 k€
Quality analysis and assessment	Depending on the entity in charge	25 days / year	25 days / year
Total			**47.2 k€ / year + 25 days / year**

Table 9: Estimated cost for the Po River

3.3.6.3. Conclusion on the Po River

Based on the analysis carried out and described in TD13 [RD28], the Po River is a location suitable for the development of FRM stations. In particular, the micro-stations installed during the project should be maintained for a long period at the three stations of Boretto, Isola Pescaroli and Pontelagoscuro. In the case of Casale Monferrato, it is recommended to move the site location upstream, to avoid the barrage effect. Regarding the procedure for the FRM, several drone flights are recommended for reliable slope estimation. The ideal case would be to have 3 profiles such as on the Garonne site: one at low level, one at medium level and one at high level. As an alternative to the drone flight, IceSat-2 data can be used for an average slope of the stretch. Another solution is the hydraulic model available for the Po River for a long stretch from Piacenza to Pontelagoscuro; different scenarios can be simulated for different flow conditions in order to obtain different slope profiles to be used in the analysis of the super sites included in the modelled stretch.

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

3.3.7. The Tiber River

3.3.7.1. Suitability of the Tiber River

The Tiber River is located in Central Italy and drains an area of 17,375 km2. It flows in a North-South direction in a single 409-km-long branch through the regions of Tuscany, Umbria and Lazio. Climatic and hydrological regimes vary from sub-coastal in the Apennines to marine in the lower basin. The Tiber River was chosen to test the potential of the Sentinel-3 altimeter in observing a river about 60 m wide and in a predominantly hilly and mountainous terrain.

Four Cal/Val super sites have been selected along the Tiber River and they are located at Santa Lucia, Umbertide, Pierantonio and Ponte Nuovo. Figure 41 illustrates the locations of the existing sensors from the regional networks, the satellite tracks, and the selected super sites. It is worth mentioning that the super sites are also equipped with stations from vorteX.io.

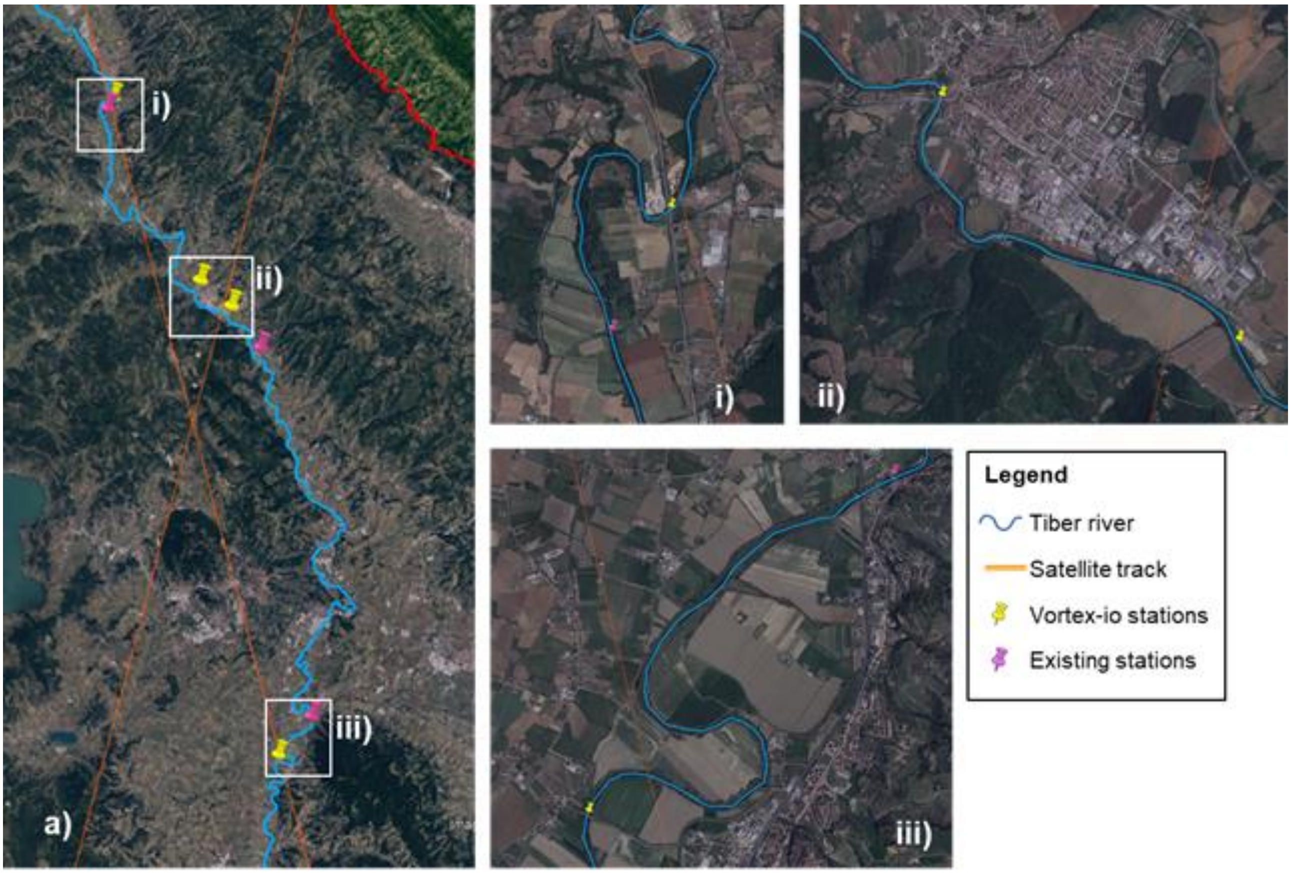


Figure 41: Tiber River - Location of the in-situ stations of the regional networks and the super sites along with the location of the Sentinel-3B tracks

3.3.7.2. Instrumentation installed on the Tiber River and associated costs

3 vorteX.io have been installed on the Tiber River: Umbertide, Pierantonio and Ponte Nuovo. At the site of Santa Lucia, the installation is currently not possible due to work in progress on the bridge. The detailed maps of the 4 sites are presented in Figure 42. Based on the site classification detailed in chapter 2.8, only the Santa Lucia site has a Complexity Level of 0. The 3 others have a complexity level of 3. A slope correction is then required on these sites. Knowing that these sites have been identified late in the project, no drone flight are planned to be performed during the St3TART project. However, 3 slope measurements are required (1 at high water level, 1 at medium water level and 1 at low water level) to compute FRM following the method described in chapter 3.2.

Figure 42: Detailed map of the instrumentation over the Tiber River. Top left: Santa Lucia, top right: Umbertide, bottom left: Pierantonio, bottom right: Ponte Nuovo

Description	Unit cost	Quantity	Cost
1 year of 4 vorteX.io Micro-Stations	4800 €/year	4 Micro-Stations	19 200 €/year
Quality analysis and assessment	Depending on the entity in charge	25 days / year	25 days / year
Total			**19.2 k€ + 25 days /year**

Table 10: Estimated costs of the Tiber sites

3.3.7.3. Conclusion on the Tiber River

The analysis done over the Tiber River is relatively recent and general conclusions cannot be drawn. However, it is obvious that drone flights are important to evaluate a reliable slope of the water surface especially because in this upper part of the river the IceSat-2 data are not available. In addition, over the super sites selected by the project, a hydraulic model is available and can be run for different flow conditions to simulate the evolution of the water surface and related slope.

3.3.8. Particular cases

3.3.8.1. Case of Estuaries

The estuaries are a highly dynamical regions where river and ocean water masses meet, resulting in a mix of various processes, such as river flows, ocean tides, storm surges and local sea level variations. The 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. The implementation of Cal/Val sites for the SWOT mission in the estuaries, have highlighted the need for very high time sampling in the in-situ measurements to be able to catch these quick variations. Furthermore, in these regions, the presence of wetting/drying areas can affect the waveforms satellite altimetry observations. The satellite measurements should be analysed to check the impact of such areas in the comparison with in-situ observations.

In the energetic environments of estuaries, the comparison between altimetry and in situ water heights shall dynamically consider the water height difference between the locations of the two measurements (in the equation below). To catch the water level dynamics over a few kilometres, the moving sensors (as GPS carpet, drones and airborne LiDAR) are too slow, very expensive and can be limited by weather conditions. In this context, models become essential to remove the aliased high-frequency dynamical signals due to the ocean tide and storm surge from the satellite altimetry measurements over estuarian regions, in order to obtain high-quality data.

$$Diff_W SH(t,C) = WSH_alti(t,C) - WSH_gauge(t,G) + \Delta WSH[river, tides, surge](t,C,G)$$

The implementation of hydrodynamic models in estuaries such as the Gironde, the Seine and the Elbe (performed by LEGOS, University of Rouen and NOVELTIS) has highlighted that the complexity of the interactions between river flow and ocean dynamics in those estuaries 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. Because of all these reasons, the installation of Cal/Val sites in estuaries is key to integrate the observations into the already existing network of tide gauges in the estuary to be used in the model assimilation scheme in future Cal/Val activities.

3.3.8.2. Case of icy rivers

The icy rivers are specific regions with a strong seasonality due to the presence of ice during the winter period. This particular case has not been addressed in this project but is of interest because of the location of these sites. Indeed, icy rivers are mainly located at high latitudes with a high sampling of the Sentinel-3 orbit. But it also represents a high complexity due to the presence of ice during the winter period which effects and impacts must be carefully analysed on the Sentinel-3 measurements before defining a strategy for an operational FRM production. This particular topic should be the subject of a dedicated study phase. To do so, a flag indicating the presence of ice, or the percentage of the iced river surface will be useful to perform this study. In-situ images of the river at each measurement can be a solution to set up this “in-situ” ice flag. Investigating opportunity sites can be dangerous if this ice flag is not provided.

4. Cal/Val super sites on lakes

4.1. Introduction on the rationale

For lake super sites, the recommended solution combines permanent sensors and periodic campaigns. The solution is described by the scheme in Figure 43. The recommended solution relies on the use of existing in-situ networks. The existing sensor data must be checked with respect to FRM standards. A GNSS calibration must be performed on the existing sensor to properly reference the precise position and the measurements of the sensor. It is also necessary to ensure that the data is accessible on a regular basis and that the time taken to make the data available is compatible with the expected latency for operational Cal/Val activities.

Existing sensors can be complemented with an automatic and connected station only if the installation of such a system is possible within the +/- 1km excursion area.

Periodic campaigns must be performed with moving sensors in order to measure the water surface height of the lake below the Sentinel-3 ground track. The objectives are double: first the periodic campaign will provide a calibration for all sensors present in the area, but the most important goal is to measure the mean lake profile in order to correct satellite measurements from local geoid errors. Indeed, TD-1 [RD6] has shown the importance of geoid errors when comparing satellite data acquired over lakes to permanent in-situ sensors, knowing that geoid models are not accurate enough over big lakes, leading to errors of several tenths of centimetres. Any of the moving sensors described in TD-1 [RD6] can be used for these periodic campaigns, the choice of sensor will be done depending on the ease of deployment on the field. In this project we choose to use the vorteX.io drone-embedded LiDAR altimeter and the towed GNSS carpet depending on the Cal/Val sites. Note that for Level 0 lakes (e.g., a small lake with negligible slope), campaigns to establish height profiles is not mandatory; a precisely calibrated gauge is sufficient.

Finally, it is important to retrieve wind speed measurements in the area at the time where the satellite observes the lake. The strong impact of water surface roughness on the radar altimeter echoes has also been demonstrated in the TD-1 [RD6]. In this context, data from local in-situ wind speed sensors must be collected and provided into the FRM products.

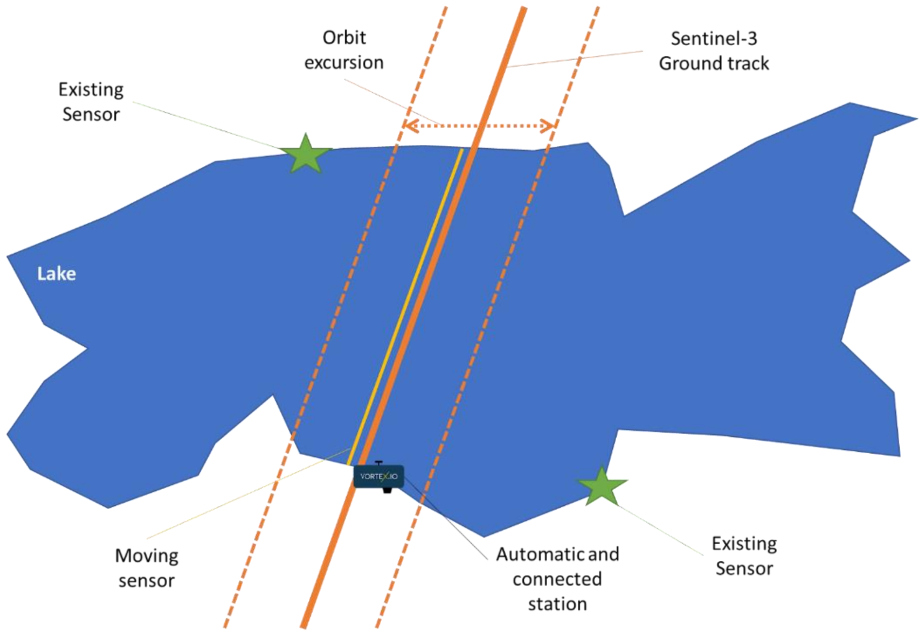


Figure 43: Scheme of Cal/Val "super site" instrumentation over a Lake

4.2. Strategy for the computation of FRM over Lakes

The strategy for lakes is based on the extensive use of existing gauge networks and the use of the Issykkul super site which has been instrumented for many years and on which operations are granted in the future as part of the SWOT

Cal/Val phase. Also, this lake is located under the 1-day orbit of SWOT, and SWOT data will provide tremendous information on the actual roughness and water height variations. That SWOT information will be of key importance to address the most challenging features encountered over large lakes and related to the actual roughness variability.

4.3. Computing FRM over the selected Cal/Val sites

4.3.1. The Issykkul Lake

The Issykkul Lake has been selected as a Cal/Val super site.

The Issykkul Lake is located in Central Asia, in Kyrgyzstan, and since 2004 more than 20 field campaigns have been carried out in the framework of the CNES TOSCA FOAM project for satellite altimetry Cal/Val for many missions: Jason-1, Jason-2, Jason-3, Envisat, SARAL/AltiKa, Sentinel-3A and Sentinel-3B.

It has a length of 180 km and a width of about 60/70 km. The surrounding landscape is very diverse, from high mountains to flat areas making it sensitive to seiche effects in some places. This quite large lake is never frozen and is covered by many nadir altimeter satellite ground tracks. The access is quite easy thanks to nearly 20 years of collaboration between LEGOS and the local Kyrgyz institute of hydrology. Vessels for navigation over the entire lake are available all year round at a reasonable price. Recent experiences have been carried out with the GPS carpet and have demonstrated again the high quality of this device to derive the height and slope of the WSE over a very long segment, making possible to analyse the local effect related to roughness variability on the altimeter data.

The Issykkul Lake is also one of the Tier-1 sites for the SWOT mission.

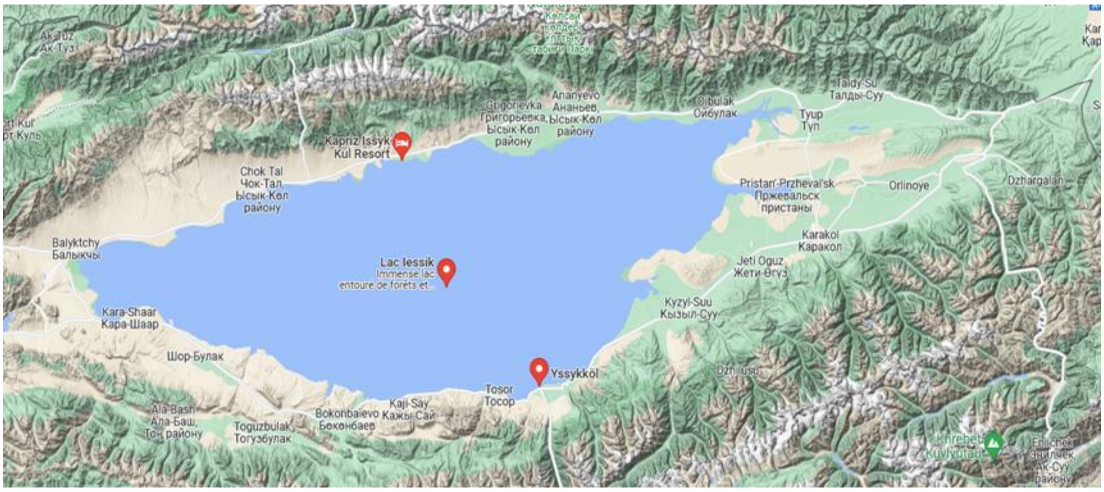


Figure 44: Map of the Issykkul Lake

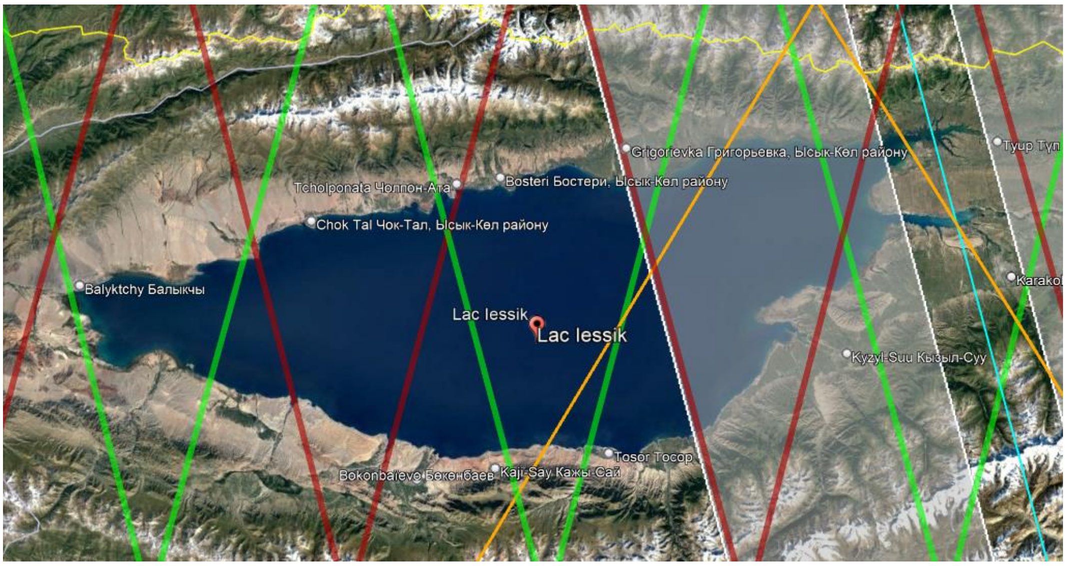


Figure 45: List of satellite tracks crossing the Issykkul Lake. Red lines: Sentinel-3A, green lines: Sentinel-3B, orange lines: Sentinel-6, light blue line: SWOT, white areas: SWOT swath

For many years, the Issykkul Lake has been instrumented with a network of different gauges. This instrumentation was deployed to better calibrate the tropospheric correction (two weather stations and two permanent GPS receivers) and to validate long-term time series of water level calculated from satellite altimetry. We also have an agreement with the Institute of Water Problems of Bishkek (IWPB) to retrieve historical in situ data to complete the validation dataset. It includes level gauges and a weather station. Those historical data, along with the lake mean surface, might be of key importance to apply the FRM approach on past missions like ENVISAT.

Regarding the principal objective of the experiment, which is to estimate the altimeter absolute bias, we have used field measurements based on GPS surveys of the lake surface along the altimetry track for each targeted satellite. The principle is to install one or two GPS antennas on top of a vessel, and to navigate along the track to measure the ellipsoidal altitude all along the satellite track as close as possible to the actual time of the satellite overflight (what we call RDV mode). Moreover, we install a radar on the boat which allows us to correct for the vessel waterline variations at different velocities. This RDV mode also allows us to cancel errors due to potential seiche effects, which may occur during the experiment. Through this procedure, if a seiche is observed during the experiment, it is naturally removed in the estimation of the altimeter bias, as both the GPS and altimeter measure this seiche instantaneously. This procedure has been applied with success in earlier studies for the estimation of Topex/Poseidon, Jason-1, Jason-2, Jason-3, Envisat, Saral/AltiKa and Sentinel-3A absolute and relative biases. In addition, we now use the GPS carpet

To determine the altimeter absolute bias, we must calculate the ellipsoidal altitude of the lake along the altimeter track by two means: from altimetry data and from the GPS receivers installed on a boat, which follows the different altimeter tracks during its cruise on the lake. The absolute bias is simply the averaged difference between both estimations along the track. It is obviously also necessary to quantify the error budget of this calculation which originates from both water altitude estimations. So, part of the uncertainty is due to altimetry errors, the other part from the GPS data processing.

For tropospheric correction we have used the weather stations data combined with the permanent GPS receiver. It has allowed us to use more precise dry and wet tropospheric corrections and to determine the level of errors made when using the models available in the GDRS (it is sub-centimetre-level for dry tropospheric correction and centimetre-level for wet tropospheric correction).

All these sensors are not fully FRM compliant, as we do not have yet implemented a real time monitoring, nor data transmission in real time. However, we have recently worked with a German institute that has started to install remote control systems over this big lake. The collaboration is very fruitful and will be further increased in the framework of the SWOT CalVal campaigns.

The results of the field campaign performed on the Issykkul lake are presented in TD-13 [RD28].

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.

4.3.2. Lakes with existing networks

In order to maximise the number of operational FRM provisions over lakes, an interesting means is to use existing sensors over different lakes managed by third-party organisations.

CNES has developed the 'LPP' system to process Sentinel-3 SAR data over lake surfaces. To ensure the validation of the performances of this new method, a large set of lakes with available in situ data has been selected. Based on the knowledge of the actual in situ data quality and trying to include various situations, the CNES team has selected the following set of lakes:

- USGS network in North America
- Ireland
- Russia
- Italy
- Brazil (Ceara)
- Madagascar

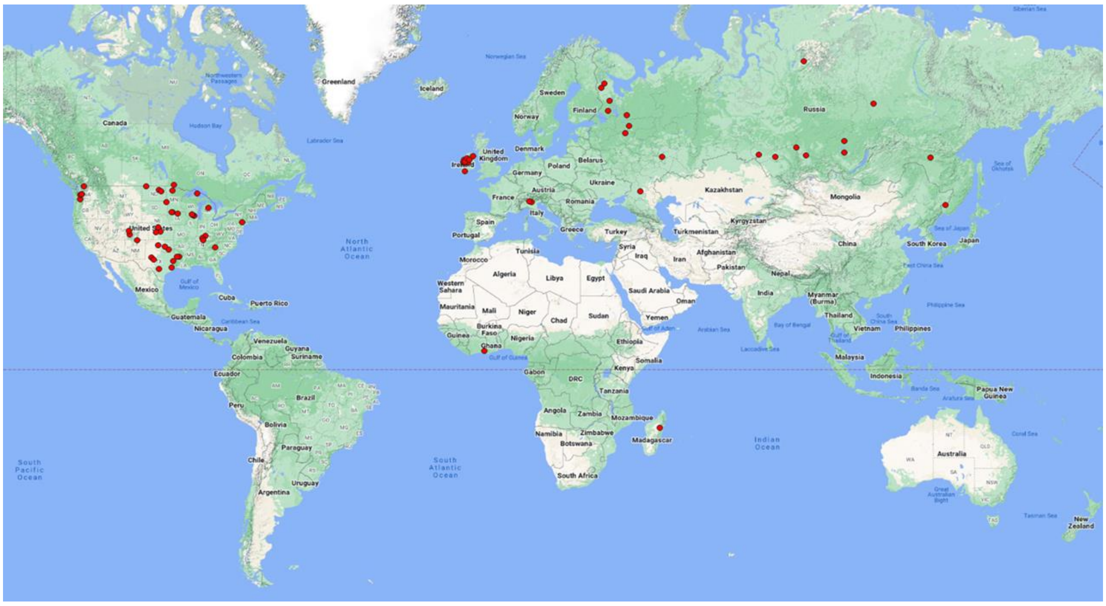


Figure 46: Map of lakes selected into the LPP database and equipped with reliable in-situ measurements

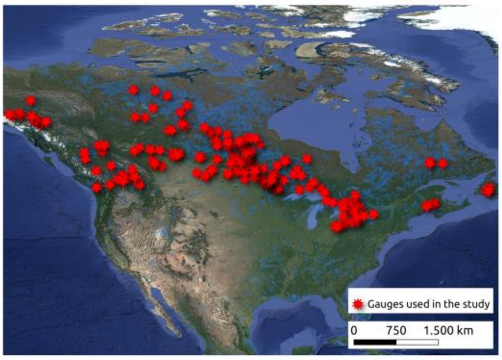
The data analysis over these lakes has not yet been completed, it will be performed in 2023 and a peer reviewed paper is planned. This will complement the one issued in 2020 by F. Boy et al.

4.3.3. Focus over US and Canadian lakes

Thanks to the study performed by Nielsen et al. in 2020 [RD24] a list of 76 US lakes has been analysed and selected. The gauge data from these lakes can be directly acquired on the USGS portal using the following link: https://waterdata.usgs.gov/nwis/sw.

The vertical reference of the gauge data is either relative or given in the American systems, The National Geodetic Vertical Datum of 1929 (NGVD29) and North American Vertical Datum of 1988 (NAVD 88).

The Canadian gauges data can be obtained from the Canadian government via the webpage https://wateroffice.ec.gc.ca/. The gauge level measurements are either provided with respect to a relative reference or the Canadian Geodetic Datum of 1928 - CGVD28. This datum is imprecise as an absolute reference and does therefore qualify as an FRM measurements without being referenced by GPS. However, the relative measurements are still of high quality and can be used to assess the relative variations of the S3 water levels in time. For the Canadian lakes 179 gauges were used to validate the Sentinel-3A /3B water level distributed over 133 lakes.



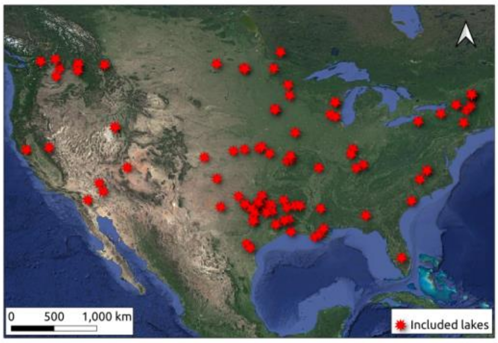


Figure 47: The location of the lakes/gauges us in the validation, left Canada, right, US

When validating the Sentinel-3 lake water level measurements several outside factors may influence the results, such as errors in the geoid model, the applied land-water mask, the presence of lake ice, distance between the gauge and the satellite track, a wrongly positioned range window.

A geoid is often used as a reference for altimetry-based lake water levels. In the official Sentinel-3 products, the EGM-2008 geoid model is provided. From ICESat-2 measurements it is easily shown that this model has errors over large lakes especially in mountainous areas. To minimise a potential error introduced by the geoid we create one time series per track.

In this analysis we apply the official Level-2 product “Enhanced measurements”, where elevations, based on the SAMOSA and OCOG retrackers, relative to EGM2008 are considered. To mask out the measurements related to the ground tracks that are within the lake area we intersect the location of the measurement with the lake mask “HydroLAKES” (Messager et al., 2016 [RD16]). For the Canadian lake evaluation, we used the Prior Lake database from the SWOT science team (Personal communication, Nicolas Picot). Additionally, for each observation we extract the occurrence value from the Global Surface Water product (Pekel et al., 2016 [RD17]). Water level times series are generated via the R-package “tsHydro” https://github.com/cavios/tshydro (Nielsen et al., 2015). A water level time series is generated for each combination of lake-track-retracker, this is to minimize the influence of potential geoid errors.

4.3.4. Focus over Swiss lakes

The FOEN (Federal Office for the Environment) operates and coordinates several water-related observation networks. It monitors the flow and quality of Switzerland's rivers and groundwater, as well as lake levels, by means of long-term observations at fixed stations and spot observations at temporary stations.

The network of the Hydrology Division of the Federal Office for the Environment concerning surface water currently provides data of 247 in-situ stations dedicated to water level. In addition to the water level, the network also measures the flow rate of rivers at 200 locations.

The in-situ station network is well maintained, and data can be easily and freely accessed through this link: https://www.hydrodaten.admin.ch/fr/messstationen_zustand.html.

All stations are correctly georeferenced but with respect to the local Swiss geoid. Figure 48 presents the location of the 247 stations dedicated to water level measurements.

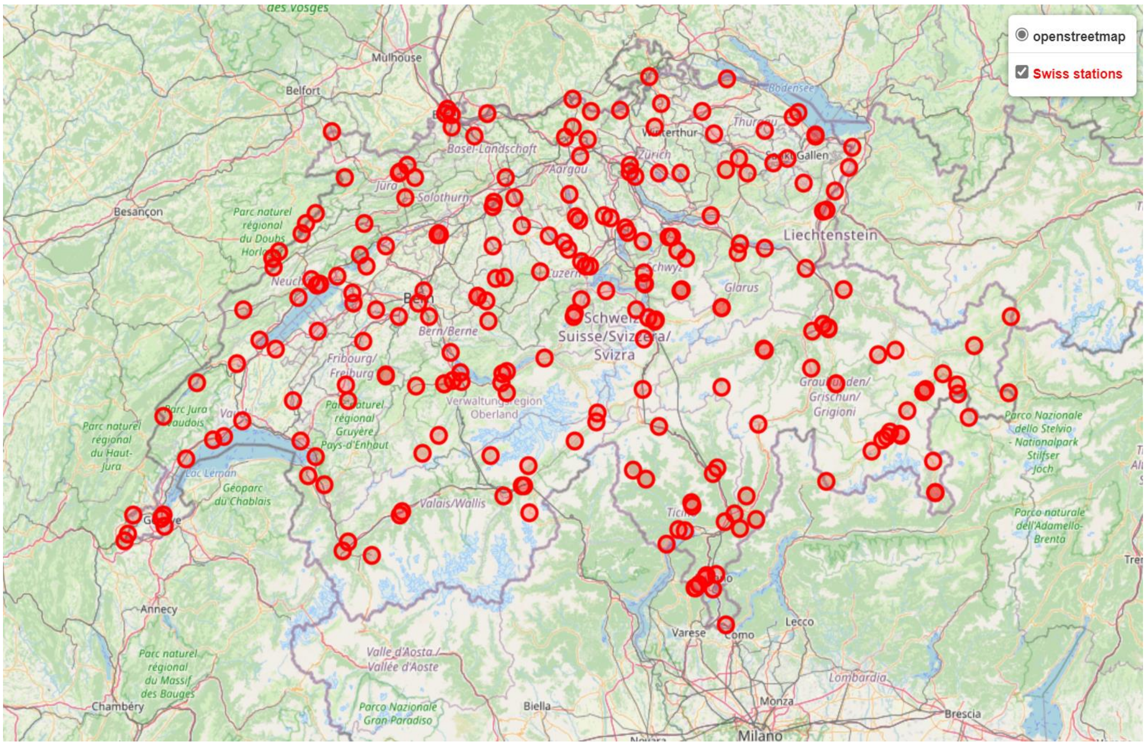


Figure 48: Map of Swiss in-situ stations dedicated to water level measurements

In TD-13 [RD28] A full statistical analysis has been performed over Swiss lakes using the public national in-situ network described above. 14 lakes Swiss lakes with Sentinel-3A/B transects and equipped with in-situ sensors are available. They are shown on Figure 49.

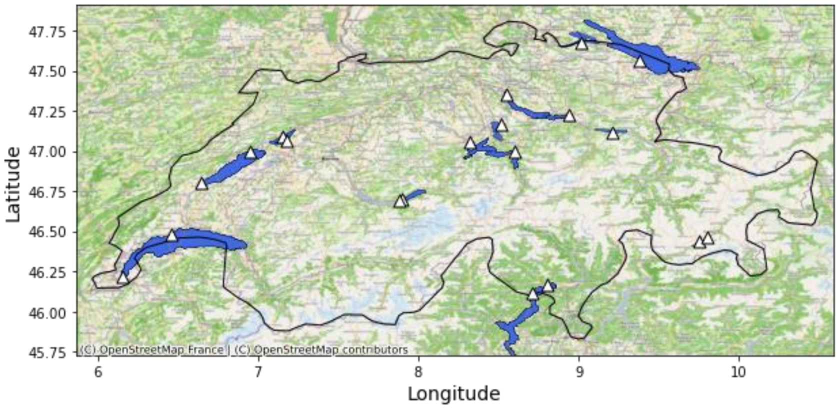


Figure 49: Map of the 14 Swiss lakes (blue areas) with S3A/B transects monitored by in-situ stations (white triangle)

The deep analysis performed on 3 different lakes (Geneva, Neuchatel and Bodensee) demonstrates the good quality of the in-situ sensors and the relevance of the statistical approach on these opportunity site with RMSE values between 10.7 cm to 28.7 cm.

5. Existing in-situ sensor networks for Opportunity Cal/Val sites

5.1. French network

The French network, also called SCHAPI, is valuable for increasing the number of FRM, as it has a large spatial coverage and long historical measurements which are comparable with Sentinel-3 data. Figure 50 present the map of all Vigicrues station located below Sentinel-3 tracks and defined in the OLTC table. A coloured marker indicates the levelled stations and station without any levelling. Opportunity site shall be selected with levelling.

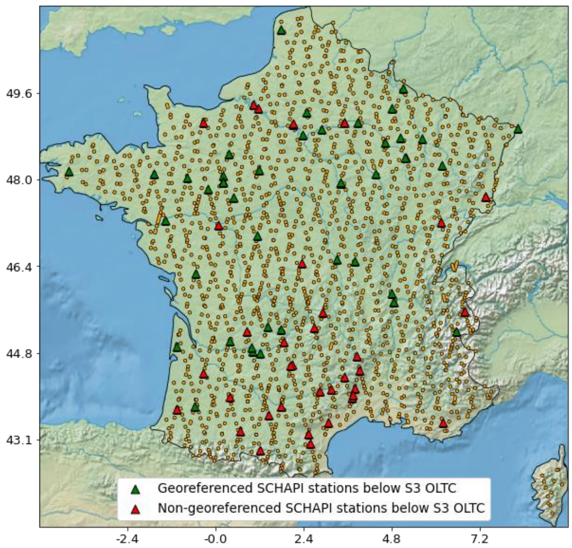


Figure 50: Map of 45 Vigicrues stations located below Sentinel-3 tracks with the altitude defined in the OLTC in green. In red, location of 45 Vigicrues stations located below Sentinel-3 tracks without any levelling

Considering the conditions listed for the opportunity sites in paragraph 2.6, three examples of SCHAPI stations have been selected among those located below the Sentinel-3 track, for which operational FRM provision is proposed. These stations are on the Adour, Aisne and Rhine rivers, and belong to different categories of Cal/Val sites (see paragraph 2.8). In the following paragraphs, the characteristics of each station are briefly described as well as the method leading to the comparison between the FRM measurements and the measurements of the in-situ station depending on the category of the Cal/Val sites. An API is available to automatically retrieve data. The documentation of this API is accessible through this link: https://hubeau.eaufrance.fr/page/apis.

The results presented in TD-13 [RD28] show very interesting performances with a RMSE of 27.9 cm when using the standard Sentinel-3 L2 products, which decreases to 15.4 cm with the thematical hydro products as shown in Figure 51.

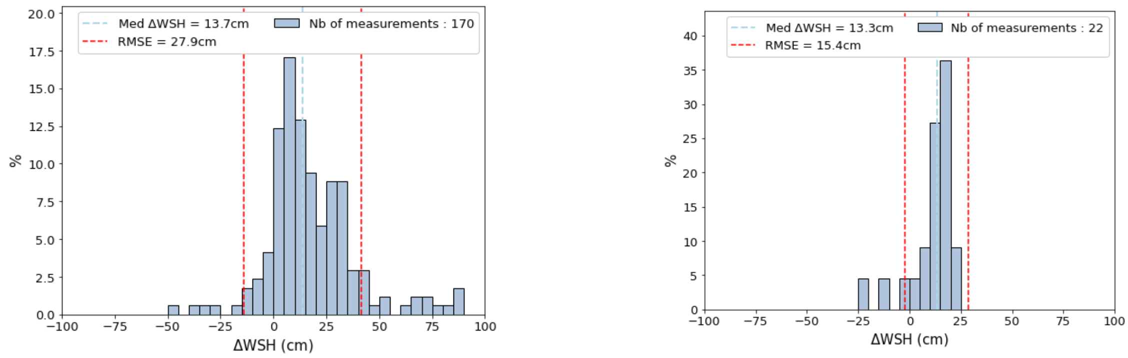


Figure 51: Histogram of the difference of WSH (ΔWSH) between S3 PDGS measurements (located at a distance shorter than 150m to the in-situ stations) and in-situ measurements (left). Histogram of the difference of WSH (ΔWSH) between S3 T-IPF measurements (located at a distance shorter than 150m to the in-situ stations) and in-situ measurements. (right)

5.1.1. Example: The Adour River

In addition to the features listed in paragraph 2.6, the station in Dax on the Adour River is proposed as an opportunity site for the following reasons:

- Low river slope (<10cm/km) according to ICESat-2 data
- Data availability since the beginning of the Sentinel-3A mission
- Not surrounded by major water bodies

The combination of these characteristics corresponds to the "Level 0" site, for which FRM measurement is simply the measurement of the SCHAPI station. In such a scenario, the FRM measurement for each cycle is compared to the nearest Sentinel-3 data to the river centreline (extracted from the Topage database). An example is shown on the map Figure 52.

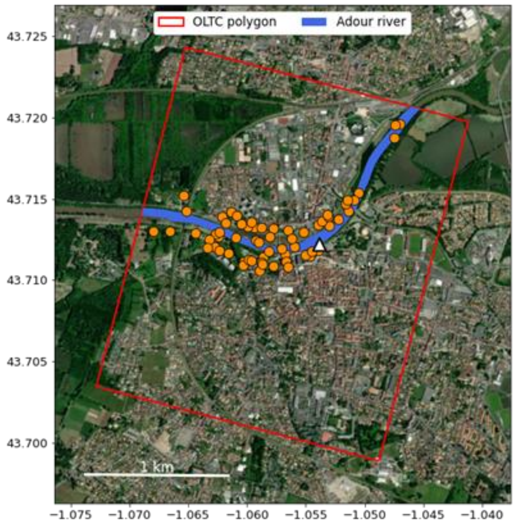


Figure 52: Selected measurements of Sentinel-3A (orange points) for all the cycles to be compared with in-situ measurements on the Adour River (blue area). SCHAPI station is represented with a white triangle.

5.1.2. Example: The Aisne and Rhine Rivers

In addition to the features listed in paragraph 2.6, the stations in Mouron (on the Aisne River) and in Lauterbourg (on the Rhine River) are proposed as opportunity sites for the following reasons:

- Relatively high value of river slope (36 cm/km for Mouron and 62 cm/km for Lauterbourg)
- In both cases, the river flows roughly perpendicular to the Sentinel-3 track, implying a potential strong POCA effect.

According to these characteristics, these two in-situ stations can be either considered as "Complexity Level 2" or "Complexity Level 3" sites and are represented in Figure 40. As there is currently no data from moving sensors giving an estimation of the river slope at different water levels, computation of the FRM is based on "Complexity Level 2" with an assumption of a river slope not evolving as a function of time and along the river.

As mentioned in paragraph 2.5, the river slope has a direct effect on the error height (see Figure 3), but also an induced effect, as it moves the POCA away from the nadir position. In theory, this combined effect is particularly high in these contexts of high river slope and across-track flow of the river and must be taken into account when comparing with FRM and Sentinel-3 measurements.

The computation of FRM is therefore composed of two additional steps relative to the Dax station on the Adour River in the previous paragraph: a correction of the slope and POCA effects.

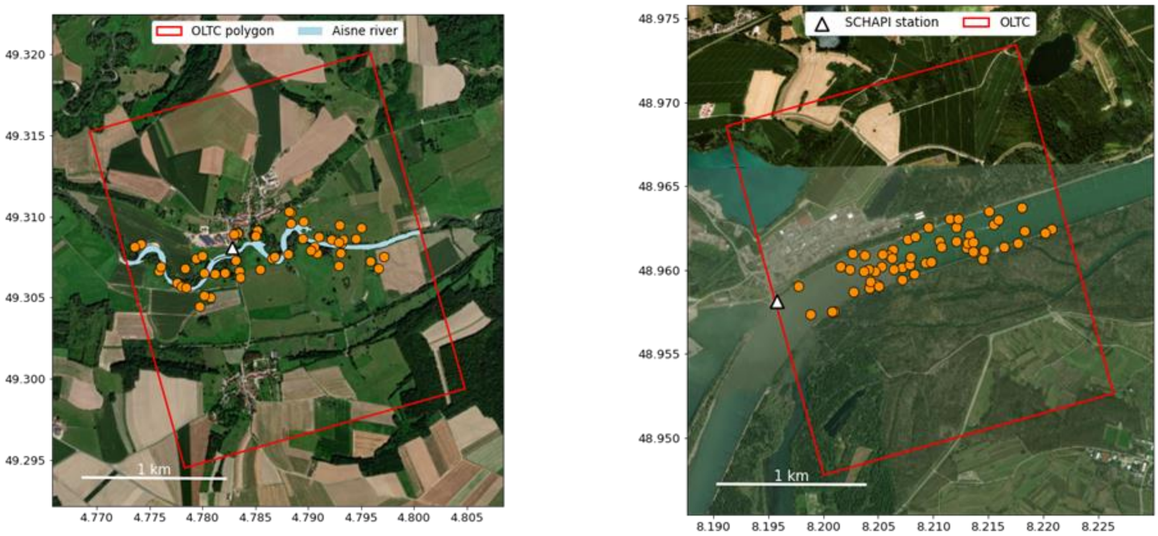


Figure 53: Selected measurements of Sentinel-3A/B (orange points) for all the cycles to be compared with in-situ measurements on the Aisne (left map) and Rhine (right map) rivers. SCHAPI stations are represented with a white triangle.

5.2. German network

From the list of existing stations described in TD-1 [RD6], GIS has analysed the quality of a set of in-situ stations located at less than 1 km from a Sentinel-3 track. After this analysis performed in the framework of the St3TART project, GIS has selected a set of 35 in-situ stations presenting a good data quality. The location of these 35 stations is shown in Figure 54. A specific focus has been made on the Rhine River but we can find other water bodies.

In the German network, the acquisition of in-situ data is somewhat complicated as the online access is either limited or not frequently updated. Therefore, retrieving specific data often requires individual requests to the German national authorities. The data is then gladly shared for study purposes and provides reliable measurements every 15 minutes. The following link offers an overview of available in-situ gauges in Germany:

https://www.pegelonline.wsv.de/gast/pegelinformationen;jsessionid=B79432CE6AB66C7EE7372049ACFAF225

Furthermore, some data from gauges in Baden-Württemberg can be downloaded from the link below. Access to specific data of this website is also limited and thus it is recommended to individually request their measurements.

http://udo.lubw.baden-wuerttemberg.de/public/p/pegel_messwerte_leer

On the Rhine River, Dutch data can be accessed on this link: https://waterinfo.rws.nl/#!/nav/themakaarten/. Hereby, several hydrological parameters can be obtained via download. In some cases, the data is limited to a specific period. More data can be requested through their contact form.

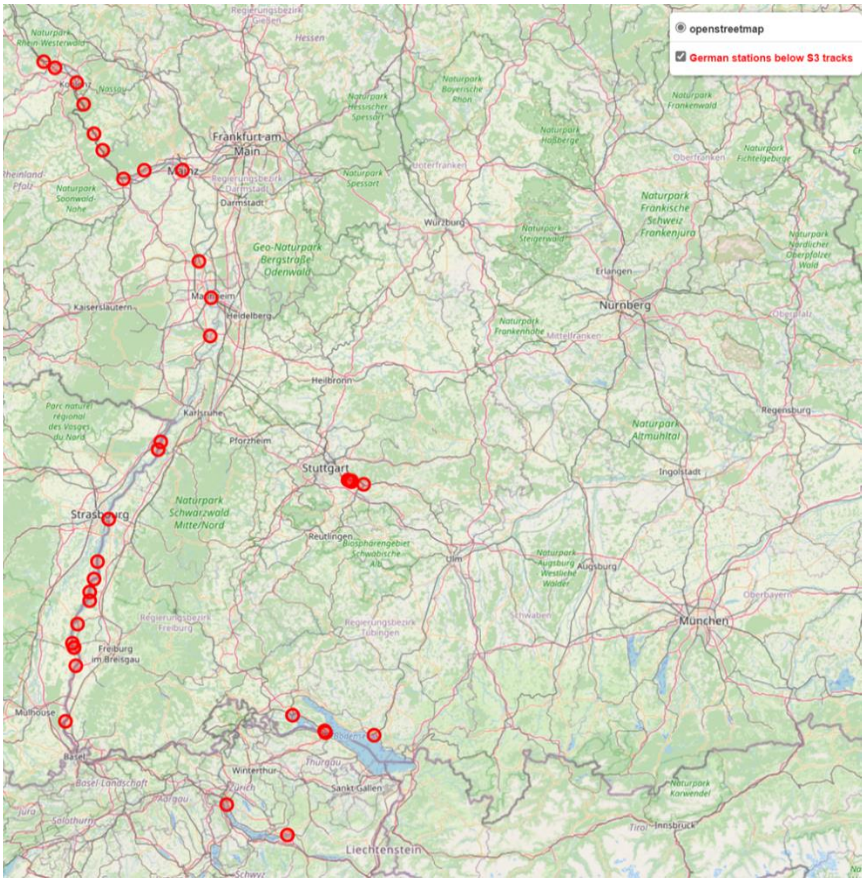


Figure 54: Map of the location of existing in-situ networks over the Rhine River (German and Dutch part)

The statistical analysis performed in TD-13 [RD28] is also summarized here to show the potential metrics that can be derived from such analysis.

	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

Figure 55: A tabular overview of three computed metrics for different opportunity sites in Germany (with additional results in Switzerland and Netherland)

5.3. Norwegian network

The Norwegian Directorate for Water Resources and Energy (NVE) provides water levels, discharge, and temperatures from about 1800 stations: https://www.nve.no/english/. The map of all available in-situ stations dedicated to water level measurements (stage) is shown in Figure 56.

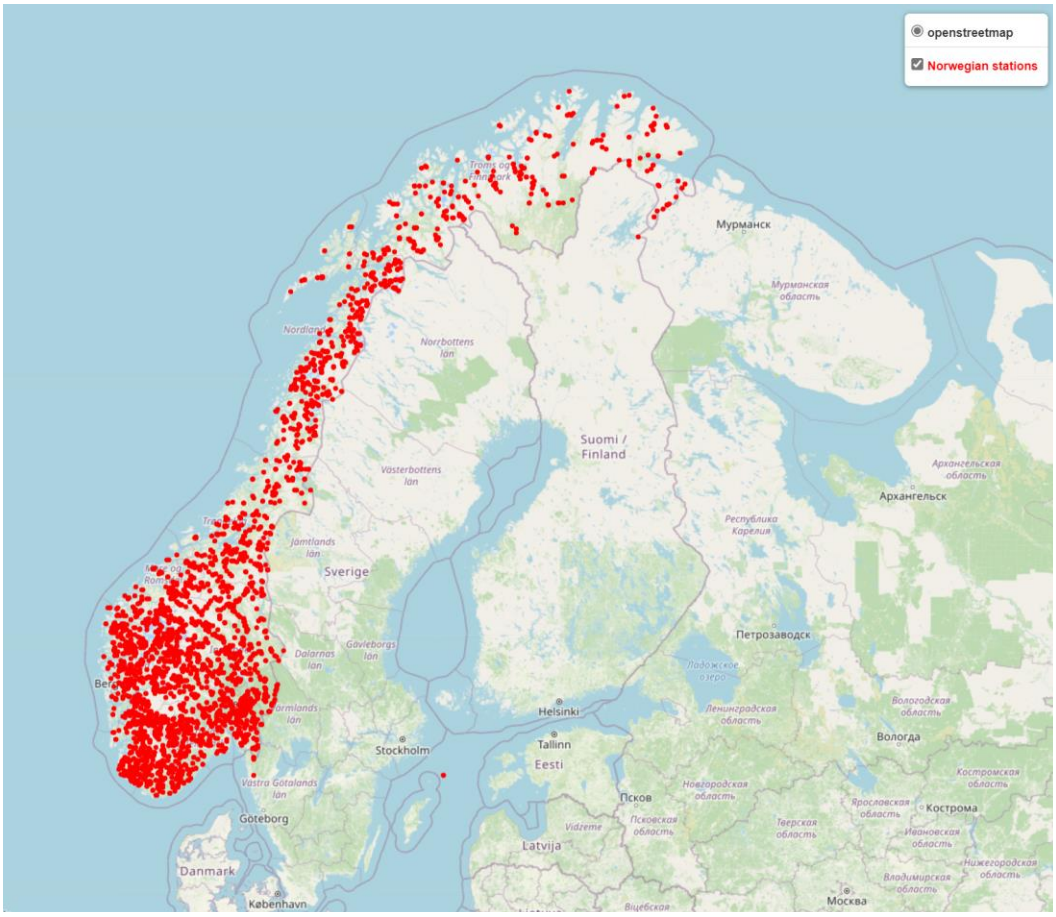


Figure 56: Map of all Norwegian in-situ stations dedicated to water level measurements.

The Norwegian network is well maintained, and data can be freely and easily accessed and downloaded on the link mentioned above. An API is available to automatically retrieve data. The documentation of this API is accessible through this link: https://hydapi.nve.no/UserDocumentation/.

Figure 57 presents the location of all Norwegian stations dedicated to water level measurements and located at less than 1 km from a Sentinel-3 track.

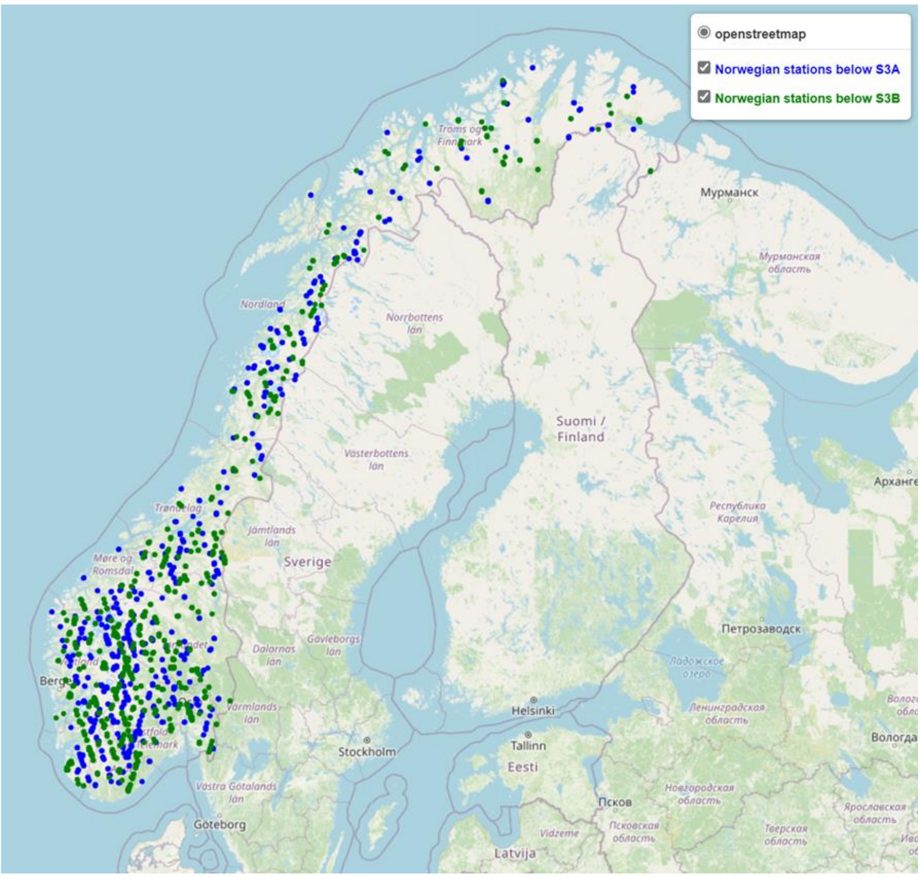


Figure 57: location of water level in-situ stations located at less than 1 km from a Sentinel-3 track

This network is of great interest because of the high number of stations and the ease of access to the data (available here https://sildre.nve.no/?params=1000&lang=en). The Norwegian network data is also available through an API: https://hydapi.nve.no/UserDocumentation/ .

This public network has not been further investigated in the frame of the St3TART project because of the icy characteristics of the rivers in Norway as explained in chapter 3.3.8.2.. This network deserves to be analysed in the future for adding more opportunity sites.

5.4. Italian network

The Italian network is managed by several agencies at regional level. ISPRA (Dipartimento per il monitoraggio e la tutela dell'ambiente e per la conservazione della biodiversità) collected data of water level and river discharge until 2018 as shown in Figure 58. The collection consists of 1276 sensors of which 747 have also river discharge measurements. Currently these data are not available due to an update of their system and we cannot perform an analysis over the Italian territory to evaluate the possible existing stations to be used as FRM. From a qualitative analysis, FRM can be set over the biggest rivers in Italy as those in Northern Italy (Po, Adige, Mincio, Oglio, Ticino, Tanaro), Tiber River and Arno

River in Central Italy. The rivers in southern Italy are characterized by lower flow with respect to the mentioned rivers and they are relatively narrow with consequent difficulties in the retrieval of the signal from the satellite.

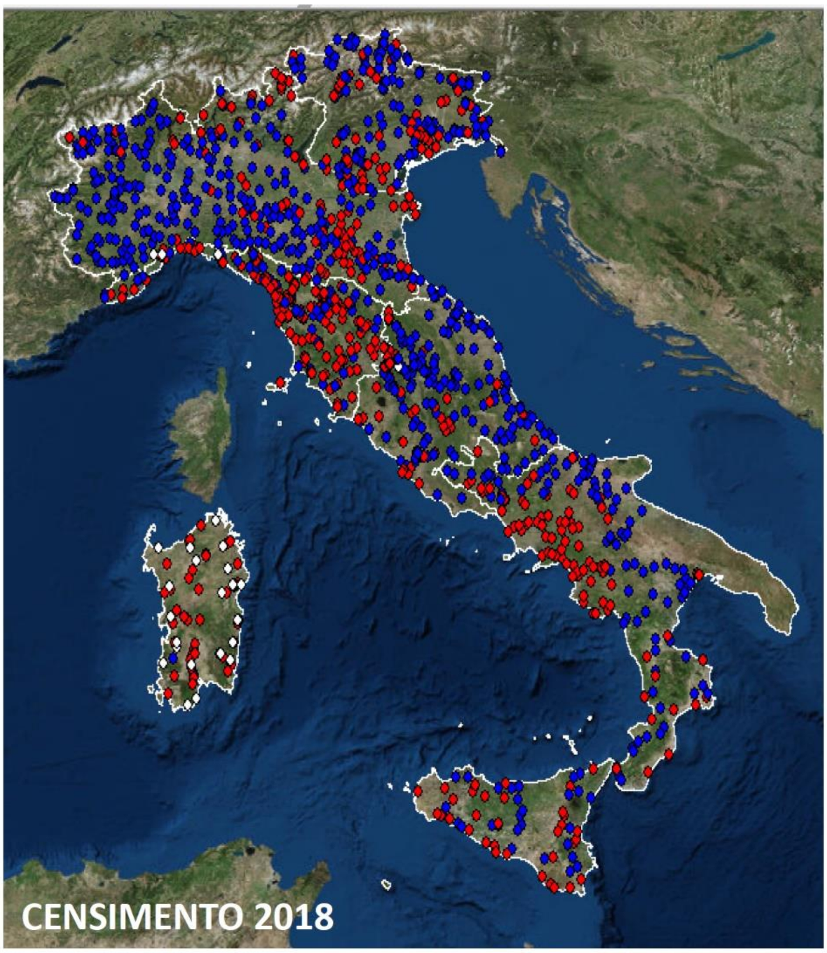


Figure 58: Census carried out in 2018 from ISPRA with measurements of water level (in red) and river discharge (in blue)

6. Metrological uncertainty analysis for inland FRM

6.1. Various FRM approach

In this project, we have mainly focused on validations against in situ measurements of water level collected via fixed or moving sensors. Examples of a fixed FRM set up are tide gauges and Vortex.io micro-stations. In some cases, a fixed FRM set up is made up of more than a single instrument. For instance, when setting up a Vortex.io micro-station, we need a GNSS station and a tape measure to calculate the exact coordinates of the micro-station. Examples of moving sensors on the other hand are GNSS carpets and drone-board lidar altimeters. Similarly, a moving FRM set up may include more than a single instrument – e.g., a lidar ranger and a GNSS receiver onboard a drone. When it comes to designing a validation scenario, an FRM may consist of both moving and fixed sensors.

Due to time constraint, some of the validation techniques appearing on the comparison diagram (see TD-1 [RD6]) were either not considered or only briefly touched upon. These include

- validation against water level measurements of other altimetry missions like Sentinel-6,
- validation against other physical quantities like discharge from in situ measurements or time series of surface water extent from satellite imagery, and
- internal validation of NRT measurements.

Notice that including the above-mentioned techniques in the comparison diagram (see TD-1 [RD6]) does not guarantee the FRM compliancy of such methods. This will remain as an interesting research topic for future studies.

6.1.1. Case of micro-station and drone-board laser altimeter for rivers

6.1.1.1. FRM set up

Figure 59 shows one of the most representative FRM set ups in St3TART for validating Sentinel-3 data over rivers. This is a section of the river Marmande monitored by Sentinel-3A relative orbit #222. The highlighted section in cyan shows the trajectory of the drone campaign conducted by Vortex.io. The three Vortex.io micro-stations are represented as MS1, MS2, and MS3.

It is important to note that the case of the Marmande is categorized as a super site. This is due to having multiple satellite overpasses (from Sentine-3A and Sentinel-6 Michael Freilich) and site-related features which allows for installing and maintaining more than one micro-station as well as implementing multiple drone campaigns.

Ideally, the micro-stations would have been installed right under the satellite overpass to measure the same water level as that of the satellite altimeter at the same time. However, the satellite overpass is subject to deviations from the nominal track and that the optimum location for installing a micro-station is not necessarily located beneath the satellite track. These conditions are very generic and not specific to the Marmande site. Hence, our team has decided to install micro-stations at a reasonable distance from the altimetry virtual station and use river profiles acquired via drone campaigns to transfer the in situ measurements of water height to the right location.

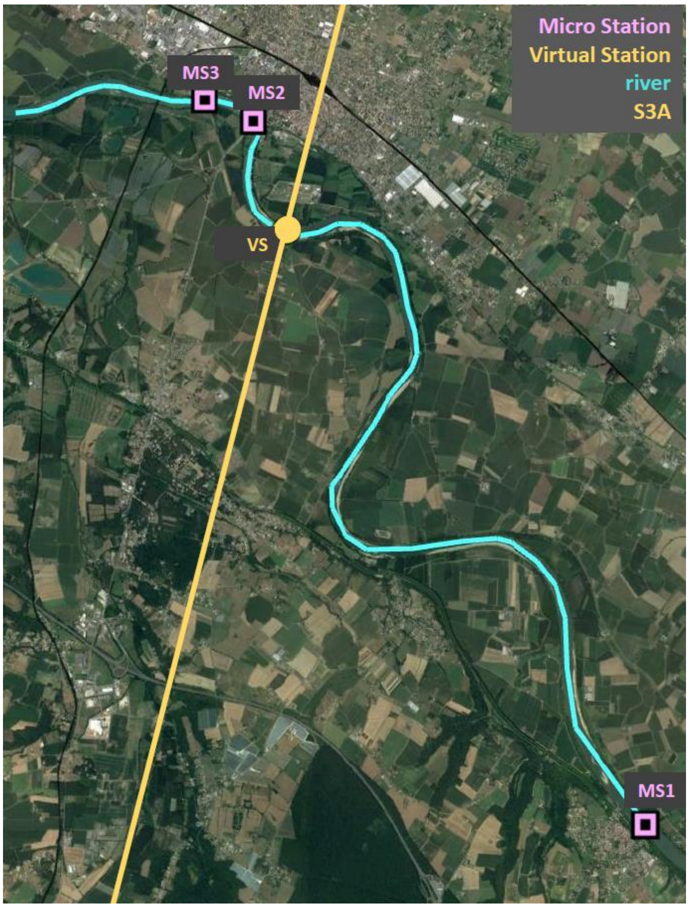


Figure 59. FRM set up using minimum of two micro-stations (MS1 & MS2) and a drone-board laser altimeter. Case of Marmande super site.

6.1.1.2. FRM Procedure

1. Drone campaign a is conducted.
2. The collected profile from drone campaign a is corrected for the fact that the whole profile is not acquired as a snapshot, i.e., the water flows as the campaign is being conducted.
   - We refer to this correction as C_{evo}.
3. Steps (1) and (2) are repeated for other drone campaigns.
   - For simplicity, we include only one more campaign in this example – campaign b (See Figure 64).
4. The water transfer time, Δt, between satellite virtual station and Vortex.io micro-station is derived.
   - Currently, Δt is considered as being a function of only the river length. In other words, we assume that the river centerline does not change in time and that the water flow is of a linear nature.
   - For simplicity, only the time transfer between VS and MS1 is used in the subsequent sections.
   - From hereafter, we denote location properties as a one-dimensional variable along the river centre line and starting from MS1 – i.e., location of MS1 is represented as $\ell_{\mathrm{MS1}} = 0$ and location of VS is represented as ℓ_{VS}.
5. The micro-station read at time $t + \Delta t$ is recorded.
   - Notice that at time $t + \Delta t$ and location MS1, the micro-station is expected to sample the same water drop as it would have sampled at time t and location VS. This is of course only true under strong assumptions.
6. Based on the water level read at the micro-station, $h_{\mathrm{MS}}(t + \Delta t)$, the closest water profiles from the drone campaign are identified, Λ_{a} *and* Λ_{b}.

- Assumptions are that we have at least two profiles, one, at higher and, one, at lower waters than that of the validation day. This is simply because we prefer to do an interpolation rather than extrapolation.

7. The FRM water level at time of flight $h_{\mathrm{VS}}^{\mathrm{FRM}}(t)$ is estimated (See the main measurement function in Figure 65).

6.1.1.3. FRM Uncertainties

The first step is to define the measurement functions. For clarity, we can define the measurement functions in a bottom-up order. The most basic measurement functions are those of the Vortex.io micro-station and that of the drone-board lidar altimeter.

- Height acquired at micro-station

Figure 60 shows the FRM set up for a micro-station under a bridge. The coordinates of the instrument are transferred from a GNSS receiver over the bridge to the micro-station under the bridge. It is assumed that the GNSS station can be set up exactly above the measurement center of the Vortex.io micro-station and that we can use a tape measure to derive this distance in a nadir manner and with a reasonably low measurement uncertainty.

Notice that the GNSS station is not permanent. Hence, the coordinates are defined at the beginning of the data collection period and calibrated later during the measurement period. The measurement function for any in situ height collected via a micro-station can therefore be described as

$$h_{\mathrm{MS}}(t') = h_{\mathrm{GNSS}}^{\mathrm{PPP}}(t') - \Delta h_{\mathrm{offset}} - \Delta h_{\mathrm{AD}}(t') + 0$$

$h_{\mathrm{MS}}(t')$ is the ellipsoidal height of water measured by the micro-station at time t'. $\Delta h_{\mathrm{offset}}$ represents the non-time-variant distance measured by the tape, and $\Delta h_{\mathrm{AD}}(t')$ describes the air draft measured by Vortex.io micro-station. To keep the equation in a generic form, we describe the GNSS height as a function of time.

It is important to notice that the micro-station and the GNSS station do not share the same sampling properties. Therefore, the discrete variable t' in the above equation, represents the air draft measurement and GNSS height after they have been resampled. This is clearly represented in the FRM uncertainty tree diagram (Figure 65), where the micro-station and GNSS stations have distinct original samplings shown by τ' and η'. Given that the GNSS station is not calibrated very often, the shared sampling of t' is expected to be a replica of τ' – the sampling of the lidar instrument on the micro-station.

The water level time series that is acquired at the micro-station can be described as

$$\boldsymbol{\Gamma}_{\mathbf{MS}} : \{\dots, h_{\mathrm{MS}}(t'_{-1}), h_{\mathrm{MS}}(t'_0), h_{\mathrm{MS}}(t'_{+1}), \dots\}.$$

The discrete indexing as shown above is selected to simplify the writing of equations in the subsequent stages. The current notation assumes that the 0 subscript represents the closest discrete sample to the desired point of evaluation.

- Estimated height for micro-station at time $t + \Delta t$

The micro-station has a sampling interval of 15 or 30 minutes, depending on the initial set up. We however are interested in the water level at micro-station at a very specific instant of time, $t + \Delta t$. It is possible to do linear, quadratic, cubic, or higher-level interpolation to estimate the height at time $t + \Delta t$ given the time series of $\boldsymbol{\Gamma}_{\mathbf{MS1}}$. As suggested by the uncertainty tree diagram (Figure 65), the linear interpolation reads

$$h_{\mathrm{MS1}}(t + \Delta t) = h_{\mathrm{MS1}}(t'_0) + \frac{h_{\mathrm{MS1}}(t'_{+1}) - h_{\mathrm{MS1}}(t'_0)}{t'_{+1} - t'_0}(t + \Delta t - t'_0) + 0.$$

t'_0 is the closest time sample at the micro-station to $t + \Delta t$ (See Figure 61).

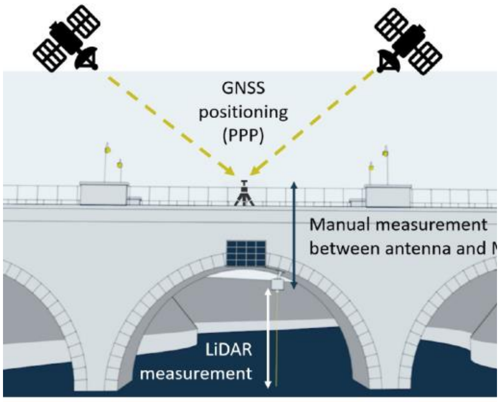


Figure 60. FRM set up for a Vortex.io micro-station

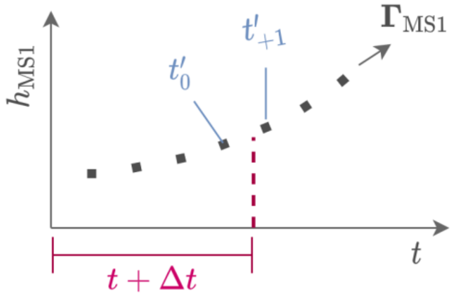


Figure 61. estimating micro-station height at continuous time $t + \Delta t$

- Height acquired by the drone

The next measurement function is that of the drone-board lidar altimeter (Figure 62). Interestingly, the measured water height can be represented with a very similar measurement function to that of a micro-station. Differences are in the Real Time Kinematic solution of GNSS, nature of the offset measurement, and the lidar instrument design. The measurement function, in this case, reads.

$$h_{\text{drone}}(t") = h_{\text{GNSS}}^{\text{RTK}}(t") - \Delta h_{\text{offset}} - \Delta h_{\text{AD}}(t") + 0.$$

Like the previous scenario, the original sampling of the GNSS height measurements and the air draft measured by the lidar instrument are not alike. Therefore, $t"$ describes the final sampling of a drone-board measurement after resampling both the GNSS measurements, $h_{\text{GNSS}}^{\text{RTL}}(\eta")$, and the air draft measurements, $\Delta h_{\text{AD}}(\tau")$. This is clearly demonstrated in the FRM uncertainty tree diagram (Figure 65).

It is important to notice that $t"$ may not be governed by only $\tau"$. Depending on the sampling features of both the GNSS system and the lidar instrument, different resampling solutions are conceivable.

The water level profile collected during the campaign drone is presented as

$$\boldsymbol{\Lambda}_{\textbf{drone}} : \{\dots, h_{\text{drone}}(t"_{-1}), h_{\text{drone}}(t"_0), h_{\text{drone}}(t"_{+1}), \dots\}.$$

- Estimated height from drone measurements at location ℓ

The trajectory of the drone flight deviates from the river centerline. Aside from this, the drone measures water level in a discrete manner. The FRM design however requires the water level exactly over the river centerline and at a specific point, ℓ_{VS} for instance. Therefore, we need to i) transfer the measured heights from the drone trajectory to the river centerline, and ii) estimate the height at the river centerline at any desired location ℓ. Figure 63 provides a schematic view of the situation. It is required that

1. all height measurements in the Λ: $\{\dots, h_{\text{drone}}(t"_{-1}), h_{\text{drone}}(t"_0), h_{\text{drone}}(t"_{+1}), \dots\}$ are corrected for the fact that the profile does not represent a snapshot of the river slope. This correction is noted as C_{evo}. See TD-1 [RD6],
2. every single sample is transferred to the closest point one the river centerline. As shown in Figure 63, the resampled measurements are not equidistant, and
3. the water level at point ℓ is estimated.

This can be done via two measurement functions. The first one projects the samples onto the river centerline and corrects for the evolution time,

$$h_{\text{drone}}(l) = h_{\text{drone}}(t") + C_{\text{evo}}(t") + 0.$$

After applying C_{evo}, the time variable $t"$ on the right-hand side of this equation disappears. This means that the collected profile is now a snapshot, and height measurements are accessible via the location samples l. The measurement function as presented here misses a term to correct for the slope along the projection line. By dismissing this term, we are imposing a very strong assumption to the $+0$ term: that the slope along all projection lines is negligible.

A second measurement function is now required to help estimate the water level at any desired location ℓ. Here we resolve the problem with a simple linear interpolation (See Figure 65):

$$\Lambda(\ell) = h_{\text{drone}}(\ell) = h_{\text{drone}}(l_0) + \frac{h_{\text{drone}}(l_{+1}) - h_{\text{drone}}(l_0)}{l_{+1} - l_0}(l - l_0) + 0$$

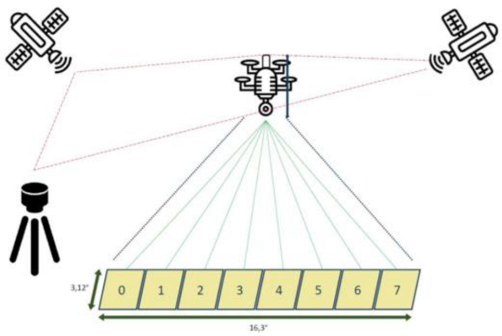


Figure 62. FRM set up of a drone board lidar altimeter

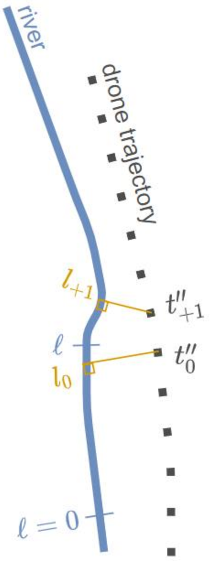


Figure 63. estimating drone-measured height at continuous location ℓ

- Main measurement function

The rationale behind the proposed FRM procedure in TD-1 [RD6] is to read the water height at time $t + \Delta t$ and location MS1, as a representative of the height of the same water drop that the satellite measures at time t and location VS. Then we need to correct for the heigh difference between MS1 and VS due to river slope. This can be described as

$$h_{\text{VS}}^{\text{FRM}}(t) = h_{\text{MS1}}(t + \Delta t) + \Delta h_{\text{slope}} + 0$$

To derive Δh_{slope}, we need to know how this correction is derived. Figure 64 depicts the input information to the derivation of the slope correction. Δh_{slope} can be described as $h_{\text{VS}}(t) - h_{\text{MS1}}(t + \Delta t)$. So far, the only unknown is $h_{\text{VS}}(t)$. Given the height of the micro-station at time $t + \Delta t$, we can select two of the most representative water profiles. The next step would be to apply a linear interpolation to estimate the height at VS at time t. Same procedure can be mathematically described as

$$\Delta h_{\text{slope}} = \hat{h}_{\text{VS}}^{\text{drone + MS1}}(h_{\text{MS1}}(t + \Delta t), \boldsymbol{\Lambda}_{\text{a}}, \boldsymbol{\Lambda}_{\text{b}}) - h_{\text{MS1}}(t + \Delta t) + 0$$

A careful look into the two equations tells us that the FRM height at VS is nothing but an estimated height using both the lidar profiles and the micro-station time series. In fact, the ultimate measurement function can be described as

$$h_{\text{VS}}^{\text{FRM}}(t) = \hat{h}_{\text{VS}}^{\text{drone + MS1}}(h_{\text{MS1}}(t + \Delta t), \boldsymbol{\Lambda}_{\text{a}}, \boldsymbol{\Lambda}_{\text{b}}).$$

While more sophisticated solutions may exist, we define the actual measurement function to be a bilinear interpolator:

$$h_{\text{VS}}^{\text{FRM}}(t) = \Lambda_{\text{a}}(\ell_{\text{VS}}) + \frac{\Lambda_{\text{b}}(\ell_{\text{VS}}) - \Lambda_{\text{a}}(\ell_{\text{VS}})}{\Lambda_{\text{b}}(0) - \Lambda_{\text{a}}(0)}\big(h_{\text{MS1}}(t + \Delta t) - \Lambda_{\text{a}}(0)\big) + 0.$$

Notice Δt is derived from the micro-station time series.

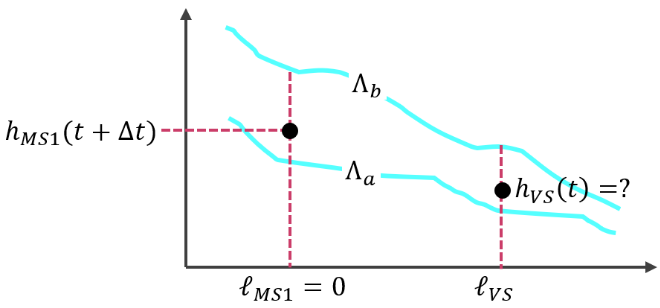


Figure 64. Deriving Δh_{slope} from lidar profiles and micro-station measurement

Remark: Towards the end of chapter 3 in TD-1 [RD6], we proposed a scheme for the validation procedure which required a clear distinction between what is described as the instantaneous height measurement at the in-situ station, $h_{\text{Inst.}}$, and what can be described as the altimetry equivalent height measurement for the virtual station, $h_{\text{Alt Equiv}}$. While any validation scenario can somehow be conceived as such, the measurement functions may not reflect such a clear step by step scheme. For instance, the proposed FRM procedure in TD-1 [RD6] inherently resolves some of the concerns about data transfer in time and space without defining them as fully separate processing procedures. Therefore, we do not refer to the same terminologies in this section.

Figure 65 represents the uncertainty tree diagram for the suggested FRM procedure as discussed so far. The main measurement function is at the heart of the diagram. This is where the bilinear interpolation is implemented to estimate the FRM height at time $t+\Delta t$. Moving away from the center of the diagram, the main measurement function is broken down to measurement functions of lower level – hence, every single component of each measurement function is linked to an uncertainty term, $u()$, which is in turn derived from another measurement function. Double-line connections and envelopes are used to avoid repetition at different instances. For example, the uncertainty in quantification of $\Lambda_a(0)$, $\Lambda_b(0)$, $\Lambda_a(\ell_{VS})$, and $\Lambda_b(\ell_{VS})$ is shown with $u(\Lambda(\ell))$. This is due to the fact that the uncertainty in quantifying all of these components are expected to be calculated the same way.

The uncertainty break-down in Figure 65 covers only the high-level procedures for this specific FRM collection scenario. The six bold arrows facing outwards are used to emphasize that the break-down should further continue. For instance, in order to quantify $u(\Delta t)$, one shall analyze the uncertainties which are involved in the derivation of Δt.

As described in TD-1 [RD6], after establishing the uncertainty tree diagrams, it is required that every identified effect is characterized via an effect table. This would allow for the estimation of uncertainty associated to the desired measurand in a fully metrological manner. All steps in this analysis requires to get properly documented.

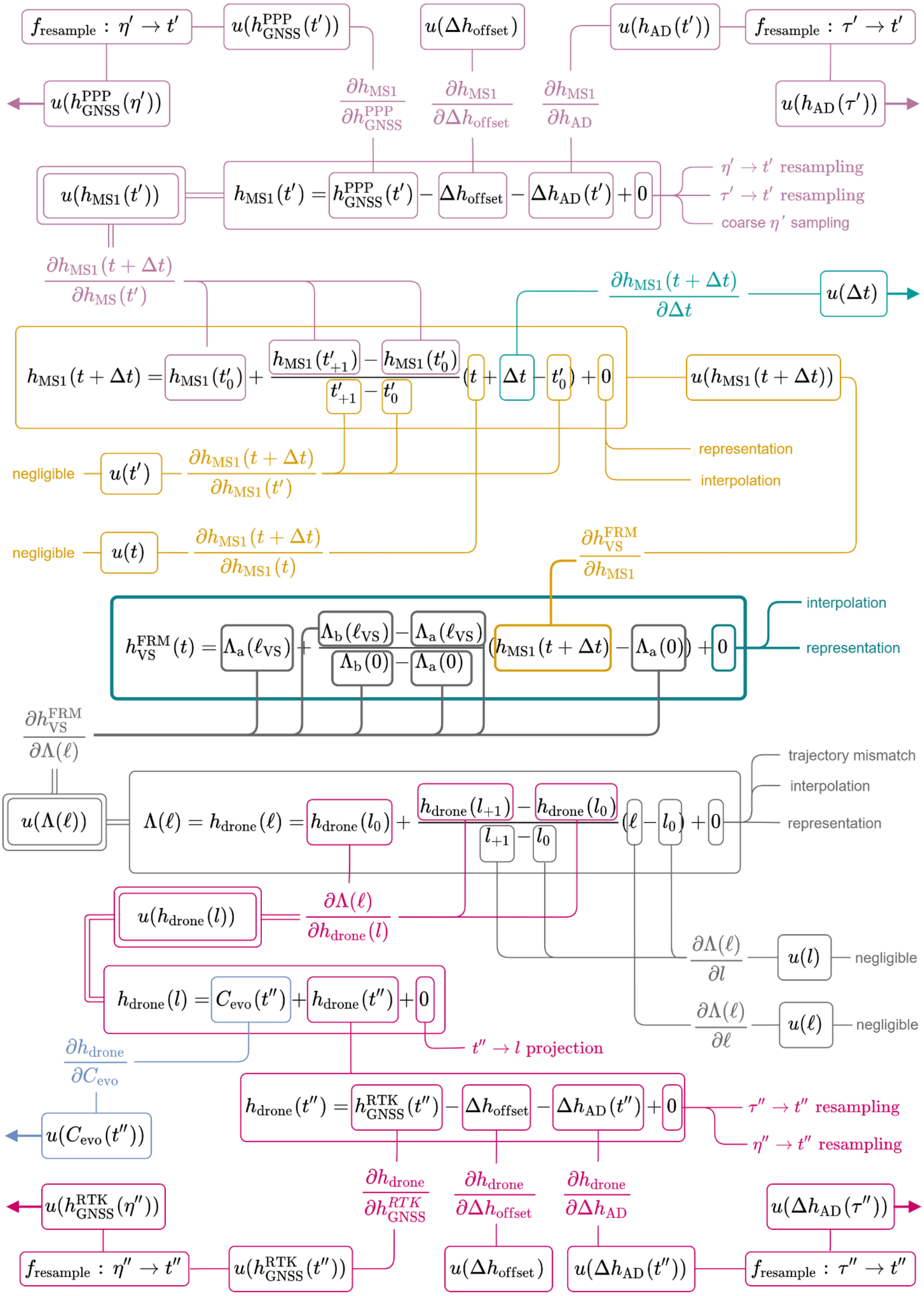


Figure 65. uncertainty tree diagram of the FRM procedures for the case of the Marmande River. Notice: the outward bold arrows show that there is a separate uncertainty tree diagram to be considered.

7. Conclusion

This document presents the Roadmap for S3 STM Land FRM operational provision for the "Sentinel-3 Topography mission Assessment through Reference Techniques (St3TART)" project. It details the different strategies, methods, processing, and sites selected and defined to ensure an operational provision of Fiducial Reference Measurements for the needs of the operational Cal/Val activities of the MPC over inland waters. This roadmap has been developed based on the requirements of the MPC to meet the MRD objectives and on the recommendation of the CCVS project. Additional discussions with the EEA helped to refine the roadmap to the document presented here.

With these bases and following the outcomes of the TD-1 FRM Protocols and Procedure for S3 STM Inland Water Products [RD6], we have defined a strategy based on the development of a set of Cal/Val super sites combined with opportunity sites.

Cal/Val super sites consist in the installation of advanced in-situ instrumentation on a set of carefully selected sites in order to ensure the operationality of the FRM production, to serve as a reference in terms of FRM quality, and to allow the analysis, exploration, and better understanding of Sentinel-3 measurements in different configurations of inland waters. A set of 8 Cal/Val super sites (Canal du Midi, Garonne River, Po River, Tiber River, Maroni River, Issykkul Lake, Rhine River on both French and German sides) have been detailed in this roadmap. These sites have been equipped and analysed during the project, and the conclusion for each site has demonstrated the validity of the approach.

Opportunity sites consist in the use of existing in-situ networks from different countries to increase the number of FRMs of opportunity on a large number of sites in order to provide statistical analysis of Sentinel-3 performance over inland waters. This document contains a non-exhaustive list of public networks that can be used as opportunity sites for the evaluation of the Sentinel-3 performances over inland waters.

The computation of FRM on each site has been detailed in a specific strategy and associated processing relying on the complexity level classification, offering a standard processing for each case. The strategy and the processing have been successfully implemented on almost all sites with very promising results.

All these activities have been supported by a metrological approach to derive the uncertainty tree diagram, allowing the computation of uncertainty for each class of the complexity level classification.

In conclusion, this document is a comprehensive work that will serve as a foundation to operationally produce Fiducial Reference Measurements to support the validation activities and foster the exploitation of the Sentinel-3 SAR altimeter Land data products over inland waters.