St3TART-FO
FRM for Sentinel-3 Land Altimetry

St3TART-FOLLOW-ON: FIDUCIAL REFERENCE MEASUREMENTS (FRM) - S3 LAND ALTIMETRY

Inland Waters FRM protocols and procedures (TD-08_1), v1.0

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afaq ISO 9001 Qualité AFNOR CERTIFICATION

Distribution list

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Document status

St3TART-FOLLOW-ON: FIDUCIAL REFERENCE MEASUREMENTS (FRM) - S3 LAND ALTIMETRY Inland Waters FRM protocols and procedures (TD-08_1), v1.0			
Issue	**Revision**	**Date**	**Reason for the revision**
1	0	22/11/2024	Initial version

Modification status				
Issue	Rev	Status *	Modified pages	Reason for the modification

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

Acronyms

AEM	Airborne ElectroMagnetic
ALS	Airborne Laser Scanner
AO	Announcement of Opportunity
API	Application Programming Interface
AWI	Alfred Wegener Institute
AWS	Automatic Weather Stations
Cal/Val	Calibration/Validation
CCI	Climate Change Initiative
CCR	Contract Close-out Review
CLS	Collecte Localisation Satellites
CIMR	Copernicus Imaging Microwave Radiometer
CO	Contract Officer
CRISTAL	Copernicus polaR Ice and Snow Topography ALtimeter
CS-2	CryoSat-2 mission
CSV	Comma-Separated Values
DOI	Digital Object Identifier
DSM	Digital Surface Models
DTU	Denmark's Technical University
EASE	Equal Area Scalable Earth
EEA	European Environmental Agency
eLTER	European Long-Term Ecosystem Research
EO	Earth Observation
ESA	European Space Agency
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
FAQ	Frequently Asked Questions
FF	Fully Focused

FFP	Firm Fixed Price
FO	Follow On
FR	Final Review
FRM	Fiducial Reference Measurement
FRM-CC	FRM Collaborative Campaign
GCOS	Global Climate Observing System
GCP	Ground Control Point
GeoJSON	Geographic JavaScript Object Notation
GIS	Geographic Information System
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GRDC	Global Runoff Data Center
IMBIE	Ice sheet Mass Balance Intercomparison Exercise
IPS	Ice Profiling Sonar
ITT	Invitation To Tender
KO	Kick Off
LEGOS	Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (literally : Laboratory of Space Geophysical and Oceanographic Studies)
LiDAR	Light Detection And Ranging
LOCEAN	Laboratoire d'Océanographie et du Climat: Expérimentations et Approches Numériques (literally : Laboratory of Oceanography and Climate: Experimentations and Numerical Approaches)
MoM	Minutes of Meeting
MPC	Mission Performance Cluster
NetCDF	Network Common Data Form
NORCE	Norwegian Research Center
NSIDC	National Snow and Ice Data Center
NPI	Norwegian Polar Institute
OLCI	Ocean and Land Colour Instrument

ORR	Operation Readiness Review
OZCAR	Observatoires de la Zone Critique, Applications et Recherches (literally: Critical Zone Observatories, Applications and Research)
PM	Progress Meeting
POCA	Point of Closest Approach
PPP	Precise Point Positioning
PR	Progress Review
PVR	Product Validation Report
QA4EO	Quality Assurance framework for Earth Observation
QGIS	Quantum Geographic Information System
QWG	Quality Working Group
RB	Requirements Baseline
REMA	Reference Elevation Model of Antarctica
S3	Sentinel-3
S3VT	Sentinel-3 Validation Team
SAR	Synthetic Aperture Radar
SBLA	Single Point Laser Altimeter
ScalSIT	Super Cal/Val Site Identifier Tool
SfM	Structure-from-Motion
SI	Système International d'unités (literally: International System of Units)
SIMS	Sea Ice Measurement System
SIN'XS	Sea Ice thickness product intercomparison exercise
SLSTR	Sea and Land Surface Temperature Radiometer
SMB	Surface Mass Balance
SNO-GLACIOCLIM	Service National d'Observation GLACIOlogique et CLIMatologique des régions de montagne (literally: National Glaciological and Climatological Observation Service for Mountain Regions)
SoW	Statement of Work
SPR	Set-up Phase Review
SWOT	Surface Water and Ocean Topography

St3TART	Sentinel-3 Topography mission Assessment through Reference Techniques (contract between 2021 and 2023)
St3TART-FO	St3TART Follow-On
STM	Surface Topography Mission
TBD	To Be Defined
TDP	Thematic Data Products
TO	Technical Officer
UAV	Unmanned Aerial Vehicles
UN	UNfocused
WP	Work Package

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[RD64]	NOV-FE-0899-NT-050	Roadmap for S3 STM Land FRM operational provision for inland waters, NOV-FE-0899-NT-050, Issue 4.1 2023, St3TART TD6

Table of contents

1 Introduction

1.1 Purpose and scope

This document is the Inland Waters FRM Protocols and Procedures initially developed for the St3TART project (2021 – 2023) and updated in this St3TART-FO project.

It presents a review of the state-of-the-art in-situ solutions, procedures, methods, Fiducial Reference Measurement (FRM) data and associated uncertainties used to assess the performance of satellite altimetry over Inland Waters.

The objective is to ensure that these observations meet the criteria of FRM standards and can be used in an operational framework. This aligns with the goals of the follow-on activities of the project (St3TART-FO), which builds on prior work to establish an operational framework to support the validation activities of the Sentinel-3 Land Topography mission.

To maintain relevance, this document will be updated as necessary throughout the project.

1.2 Overview of this document

In addition to this Introduction chapter, this "FRM Protocols and Procedures" document includes the following chapters:

- Chapter 2: The altimetry measurement for hydrology
- Chapter 3: Calibration-Validation framework for inland waters
- Chapter 4: Requirements for CAL/VAL altimetry measurements for hydrology
- Chapter 5: Means for CAL/VAL activities
    - State of the art of existing sensors with ranking and discussion on their FRM compliancy
    - Existing networks, surveys and campaigns
- Chapter 6: Learnings from alternative satellite missions
    - Review of the state-of-the-art validation methodologies
- Chapter 7: FRM Protocols and Procedures
    - Calibration site selection
    - Potential FRM sensors for S3 LAND STM L2 product validation
    - Technical plan for ensuring full traceability of the FRM data processing chain

1.3 Definition of FRM and a metrological approach

The Quality Assurance framework for Earth Observation (QA4EO), established and endorsed by Committee on Earth Observation Satellites (CEOS), defines the following principle regarding Earth Observation data quality:

> *'It is critical that data and derived products are easily accessible in an open manner and have an associated indicator of quality traceable to reference standards (preferably SI) so users can assess suitability for their applications i.e., 'fitness for purpose'.'*

QA4EO defines high level processes to achieve this, such as well-documented procedures, participation in comparisons and uncertainty assessments that apply to all EO data records. Traceability requires that this quality indicator be based on "a documented and quantifiable assessment of evidence demonstrating the level of traceability to internationally agreed (where possible SI) reference standards." The QA4EO principle stops short of requiring SI-traceability in all circumstances, recognizing that the full rigor of linkage to SI may not be viable for all applications and measurements, however, the accompanying guidelines are based on metrological concepts adapted from guidelines of the international metrology community and a metrological approach is strongly implied.

Metrology, the science of measurement, is the discipline responsible for maintaining the International System of Units (SI) and the associated system of measurement. It is core to the SI that measurements are stable over centuries and that measurement standards are equivalent worldwide. These properties are achieved through the key principles of metrological traceability: uncertainty analysis and comparison. These same principles are important to Earth observation.

The term “fiducial reference measurement” (FRM) is used for non-satellite observations that follow QA4EO guidelines.

> *Fiducial reference measurements (FRMs) are a suite of independent, fully characterized, and traceable sub-orbital measurements that follow the guidelines outlined by the GEO/CEOS Quality Assurance framework for Earth Observation (QA4EO) and have value for space-based observations.*

Thus, FRMs are the quality-assured non-satellite observations that can be used to calibrate and validate satellite-based sensor measurements. As ESA states ‘these FRM provide the maximum return on investment for a satellite mission by delivering, to users, the required confidence in data products, in the form of independent validation results and satellite measurement uncertainty estimation, over the entire end-to-end duration of a satellite mission.’

Other satellite observations cannot be considered FRMs under this definition, but satellite-based comparisons are important in the calibration and validation of satellite missions. However, a satellite-based comparison should also be considered metrologically, following many similar approaches. Similarly, comparisons with model outputs (i.e. reanalyses) are also used in Cal/Val processes, but are not FRMs.

2 Altimetry measurement for hydrology

2.1 Principle

Even if radar altimetry has been originally designed to observe and measure ocean surfaces, it is now commonly used to provide long-term monitoring of inland water levels in complement to or for replacing disappearing in situ networks of gauge stations. With Sentinel-3 missions, satellite altimetry over inland waters enters a new era. A large number of continental water bodies are now well tracked by the altimeter thanks to the on-board DEM (Le Gac et al. 2019 [RD4]). Then the altimeter performances have been largely improved with the use of delay-doppler altimetry technique which allows to complete and go further the previous Low-Resolution Mode (LRM) satellite observations. Indeed, SAR altimeters have reduced the radar footprint, and thus decrease the noise of the radar waveform compared to LRM altimeters. All the improvements brought by the Sentinel-3 satellites allows to reach an accuracy never obtained before with satellite altimetry.

In the context of an upcoming supply of Sentinel-3 products dedicated to inland waters and estuaries, the St3TART project is aimed at preparing a roadmap and providing a preliminary proof of concept for the provision of Fiducial Reference Measurements (FRM) in support of the validation activities of the Sentinel-3 (S3) radar altimeter over land surfaces of interest, i.e., inland water bodies (lakes, reservoirs, rivers including estuarian areas). Typically, St3TART and its follow-up activities should ensure a supply of fiducial data for the Cal/Val activities of the ESA S3 Mission Performance Centre/Cluster and of the S3 Validation Team.

In this chapter, we perform a review of the different uncertainty sources of the altimetry measurements over inland waters in order to identify the main Fiducial Reference Measurement to provide in the frame of the St3TART project.

Radar altimetry over inland water is a technique allowing to retrieve the surface height based on the difference between the altitude of the satellite on its orbit above the reference ellipsoid (h_{sat}) and the distance between the satellite and the surface or the altimeter range (R_{Alt}) following the scheme presented in Figure 1. The satellite altitude is accurately estimated at centimetre level using precise orbit determination techniques and the range is derived from the two-way travel time of the electromagnetic wave emitted by the sensor (Δt) considering a velocity equal to the speed of light in vacuum (c) (Chelton et al. 2001 [RD5]):

$$R_{Alt} = \frac{c\Delta t}{2}$$

Several corrections to the range are applied to consider propagation delays due to the presence of the atmosphere and geophysical effects. Over inland water bodies, the surface height is given by Crétaux et al. 2017 [RD6]:

$$WSH = h_{Sat} - \left(R_{Alt} + \Delta R_{iono} + \Delta R_{dry} + \Delta R_{wet} + \Delta R_{SolidEarth} + \Delta R_{pole} + \Delta R_{load}\right) - N_{Geoid}$$

where WSH is the orthometric height of the water surface, ΔR_{iono} is the range correction due to the ionosphere, ΔR_{dry} is the range correction due to the dry troposphere, ΔR_{wet} is the range correction due to the wet troposphere, $\Delta R_{SolidEarth}$ is the range correction due to crustal vertical motions, ΔR_{pole} is the range correction due to the pole tide, ΔR_{load} is the range correction due to the loading tide effect and N_{Geoid} is the height of the geoid with respect to the reference ellipsoid.

This equation assumes that there is no "Sea State Bias" equivalent effect over the inland water bodies which is the case except for large lakes and estuaries. Over estuaries, other effects must be accounted for and are briefly described below.

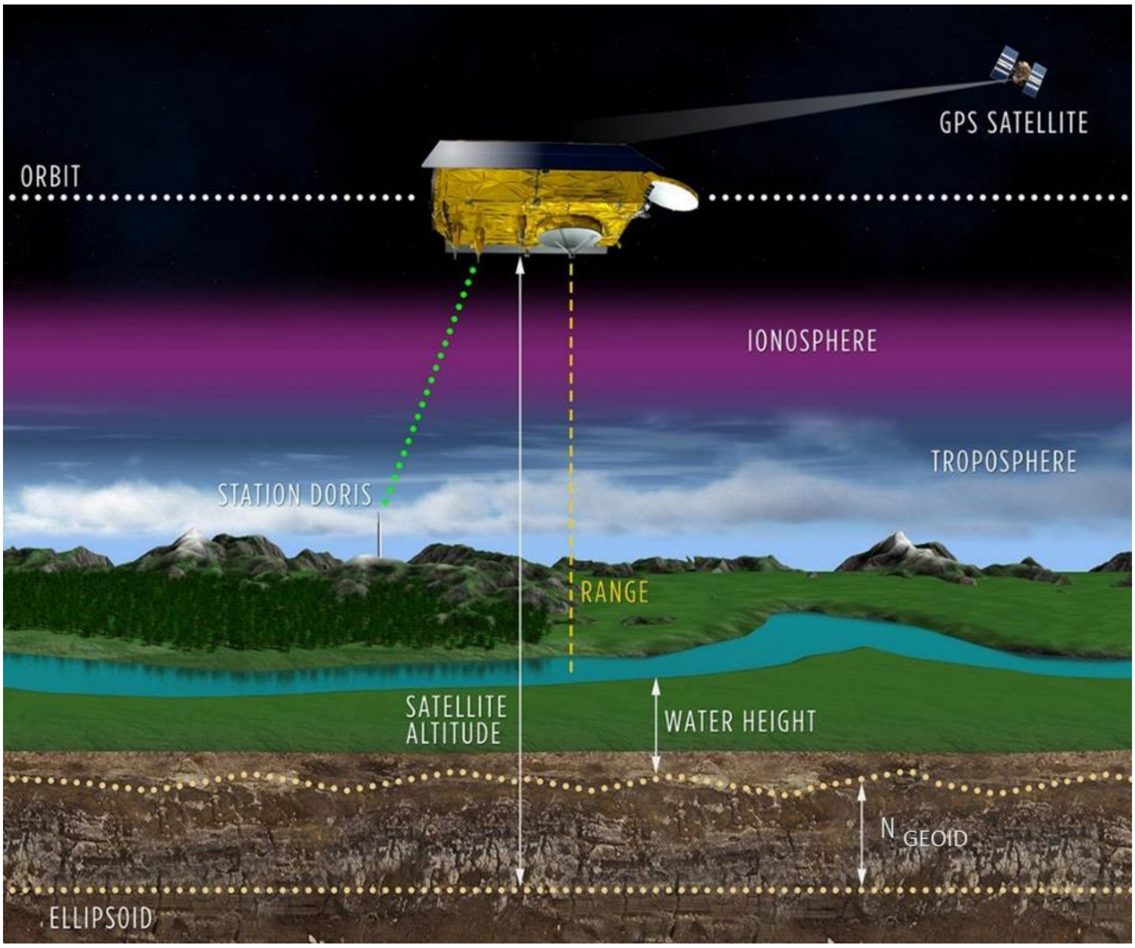


Figure 1: Principle of satellite altimetry measurements over inland water

2.2 Main challenges & uncertainty budget

As presented in the previous chapter, the altimetry measurement over inland water is impacted by different effects that must be accounted for to provide valuable water surface height measurements. The different contributors are listed and discussed below.

2.2.1 Range estimation

From high PRF individual pulses acquired by the SRAL radar altimeter, an unfocused SAR processing is on-ground applied to build an along-track improved resolution radar echo (320m along-track resolution, 450 in case Hamming weighting function is applied). From radar echoes, the range measurement R_{Alt} is computed using a retracking algorithm which aims at estimating accurately the time when the echo is received (epoch) inside the window. The range is then simply computed adding the epoch estimation to the window delay (instrumental parameter provided by the radar which corresponds to the time when acquisition window starts). Range estimation accuracy and precision are, consequently, directly linked to the quality of epoch estimation and to the retracking algorithm used.

Up to now, OCOG (Wingham, 1986 [RD7])(Xiao, 2017 [RD8]) is one of the most used standard GDR retrackers for hydrology (Nielsen, 2020 [RD9]), even if it has acknowledged limits. This is an empirical retracker which computes the epoch from the centre of gravity of the power integral of the radar echo. OCOG is very sensitive to the echo shape, which can change, for example, depending on the water body geometry. It is obvious that the radar echo will be different between a small canal and a large lake. Even over a large lake, depending on wind conditions, the surface roughness can change the radar echo shape. As OCOG is based on an empirical static relationship between power integral of the radar echo (correlated to radar echo shape) and epoch, this algorithm has a high uncertainty. In addition, multi-peak echoes are often observed, resulting from several water bodies responses received by the radar altimeter. In those situations, OCOG is often trapped by wrong signals and provides an epoch with an error of several metres.

Range estimation precision and accuracy can be widely improved using a physical-based model. It is of the highest importance to develop a new retracking algorithm that better models the radar echo signal to achieve better performances. Recent works conducted by CNES/LEGOS aim at characterizing the physics behind the interaction between radar signal and inland water surface. The objective is then to build a generic model, applicable to whatever is the water body (lake or river). This new approach will be very close to the current one applied over ocean but adapted to inland waters problematic [RD53]. Currently, it is agreed that the radar backscattering over small inland water bodies (few hundred of metres) are mostly specular. This regime is well described by (Abileah, 2017 [RD10]). It considers no or very low surface roughness. In that case, the surface acts like a mirror and a very small portion (Fresnel area is 188m for Sentinel-3, very small with respect to the first 1.8km diameter range cell) backscatters the radar signal. Simulations of specular cases show radar echo is very similar to the radar impulse response ($sinc^2$). Analysis of Sentinel-3 real data over several targets, from canals to 100m-200m wide rivers confirm this theory. To process specular echoes, a $sinc^2$ based model will provide very high precision and accuracy range estimates. However, specularity can be broken when surface roughness happens, and radar echoes shape differ from a $sinc^2$ model with a slight trailing edge. How to process those echoes optimally? Which physics better model surface roughness? Such questions are under investigation now at CNES/LEGOS.

2.2.2 Geoid Height

The error related to the geoid model is highly geographically dependent, depending on the actual geoid short scale feature that are not currently included in the geoid model solutions (spherical harmonic development). Over the ocean surfaces the use of the Mean Sea Surface information allows to largely reduce this error.

The same approach has been used by M. Berge-Nguyen et al. [RD52] over big lakes where a ‘Mean Lake Surface’ is computed by merging all available datasets. It must be pointed out, though, that Mean Lake Surfaces, which constitute an equipotential surface of the gravity field at altitude, are generally not parallel to the geoid. Hence, the orthometric height of the lake surface is not constant. This question, that seems to be undocumented in the literature on inland altimetry, is currently under investigation at GIS. The excursions from a constant orthometric height level depend on the altitude of the lake and on gravity variation on the lake surface. Preliminary quantification of this effect indicates that such excursion may amount to up to 10 cm.

Using Mean Lake Surfaces in order to compensate the deficiencies of the employed geoid model is feasible, though with the side-effect that the aforementioned orthometric height variation is cancelled at the same time. That means geometrically that the geoid will locally be forced to become parallel to the lake’s equipotential surface. Again, the consequences of such strategies are under study at GIS.

Over land surfaces where those surfaces are not available, the error can be large and reach several decimetres. For example, Hirt C (2011) [RD12] has analysed the accuracy of the EGM2008 model over Germany using a dense network of local in situ data and has demonstrated that the for quasigeoid heights, the comparisons show a RMS (root mean square) agreement of ~3 cm between EGM2008 and GCG05 as well as EGM2008 and GPS/levelling.

Several external evaluation studies on EGM2008 have already been carried out using ‘ground-truth’ gravity field observations over several countries (Newton’s Bulletin 2009 [RD13]). The comparisons made in the studies presented in Newton’s Bulletin (2009) provide evidence of low EGM2008 omission errors, i.e., the uncertainties of EGM2008-derived functionals, particularly over areas where EGM2008 is based on dense gravity data sets. Because of its high spatial resolution and accuracy, EGM2008 represents a large part of the gravity field spectrum.

Beyond its resolution, that is at scales finer than ~5’ (~9km), EGM2008 is not capable of representing the high-frequency constituents of Earth’s gravity field. The neglect of high frequency content by a harmonic model like EGM2008 is known as omission error (Torge 2001 p. 273 [RD14]; Gruber 2009 [RD15]). For quasigeoid heights derived from EGM2008, Jekeli et al. (2009) [RD16] estimated the EGM2008 omission error to be ~4 cm. This is a global estimate which may vary for different types of terrain, and which obviously depends on gravimetric data distribution.

For areas with rather scarce surface gravity coverage (for instance, parts of Africa, South America and Asia), omission errors for EGM2008 quasi/geoid undulations are estimated to be at the level of ~15cm with maximum uncertainties encountered in the mountainous parts of Asia and South America (around ~30-40 cm) and Antarctica (~100 cm). In contrast to this, the lowest omission errors are found over most parts of Europe, Oceania, North America and – because of the use of dense sets of altimetry-derived gravity – the oceans (see Pavlis et al. 2008 [RD17]). For those regions with high-quality surface gravity available, the EGM2008 quasi/geoid omission errors are mostly at the level of ~5 cm. A detailed map of the EGM2008 quasi/geoid omission errors over Germany is shown in Figure 2 below, where the error estimates range from 3cm to 10 cm, with a rms of 3 cm.

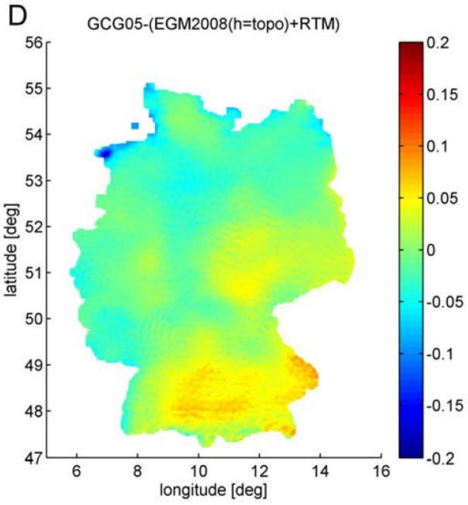


Figure 2: Detailed map of the EGM2008 quasi geoid omission errors over Germany (unit in metres)

M. Berge-Nguyen et al. [RD52] has analysed the error using its own Lake Mean Surface and reached the same conclusion in Figure 3.

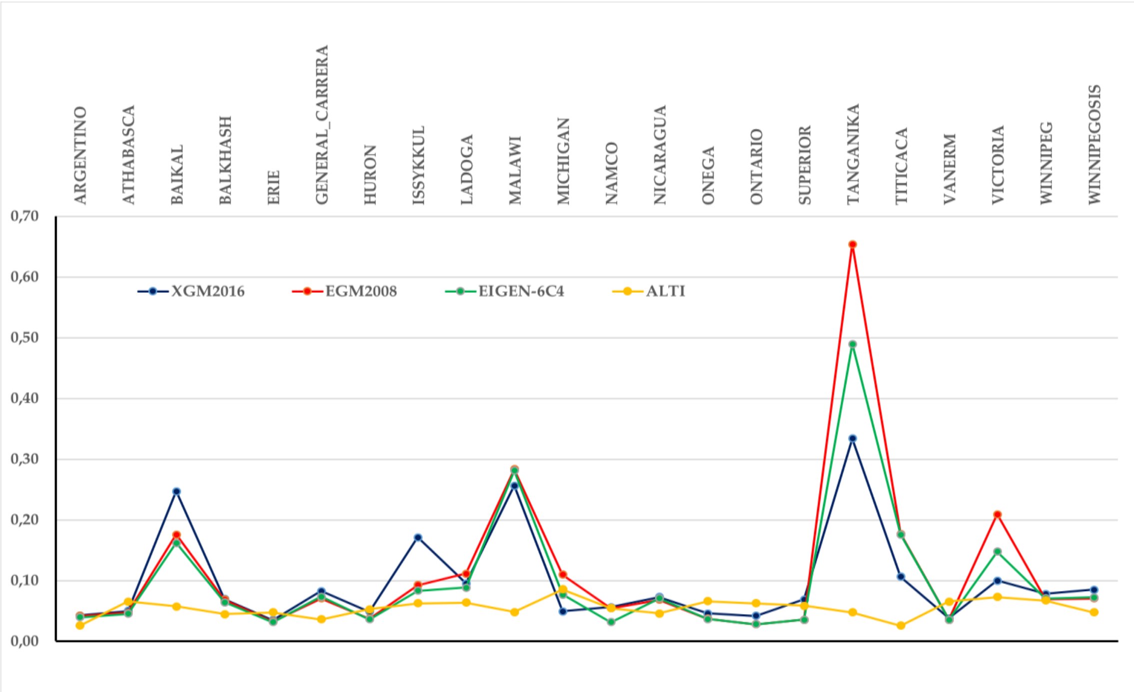


Figure 3: Error on different geoid (XGM2016 in blue, EGM2008 in red, EIGEN-6C4 in green and the mean lake profile computed using altimetry in yellow) with respect to mean lake profiles computed on several lakes

However, the impact is very small (negligible) if we have a sensor very close to the actual theoretical ground track (i.e. within +/- 1km).

2.2.3 Pole tide, solid Earth tide and loading tide

2.2.3.1 Pole tide

Satellite altimeter surface height observations include the geocentric displacements caused by the pole tide, namely the response of the solid Earth and oceans to polar motion. All altimetric missions are currently using the model developed by Desai & al in 2015 [RD18]. In this published paper, Desai has implemented two improvements to the pole tide model for satellite altimeter measurements. Firstly, an approach that improves the model for the response of the oceans by including the effects of self-gravitation, loading, and mass conservation. Secondly the displacement of the solid Earth due to the load of the ocean response, and the effects of geocentre motion. Altogether, this improvement amplifies the modelled geocentric pole tide by 15%, or up to 2 mm of surface height displacement if compared to the previous version of the model. They have validated this improvement using two decades of satellite altimeter measurements demonstrating an accuracy of the order of 1mm or less.

2.2.3.2 Solid Earth tide

For the solid earth tide and pole tide effects, the official mission products are based on the best model available today. Based on the Jason-3 ATBDs [RD19] document (approved by the altimetry community) we can state that the accuracy of the solid earth tide height is better than 1 mm (GEN_ENV_TID_03 - To compute the solid earth and the equilibrium long period ocean tide heights)

2.2.3.3 Loading tide

Ocean tide loading is the deformation of the Earth due to the weight of the ocean tides. The water in the ocean tides moves back and forth and these mass redistributions cause periodic loading of the ocean bottom. Since the Earth is not completely rigid, it deforms under this load, and this is called ocean tide loading. The impact is larger over the ocean surfaces but is not null over land and decreases as a function of the distance to the coast.

One solution to analyse the loading tide precision is to perform a comparison between two independent solutions. This is done in Figure 4 which highlights the differences between FES and GOT loading tides values over the ocean (left) with a mean value very close to 0 for the open ocean and reaching a few millimetres in some coastal areas and for the M2 tide components over land (right) with amplitudes of the order of a few millimetres locally.

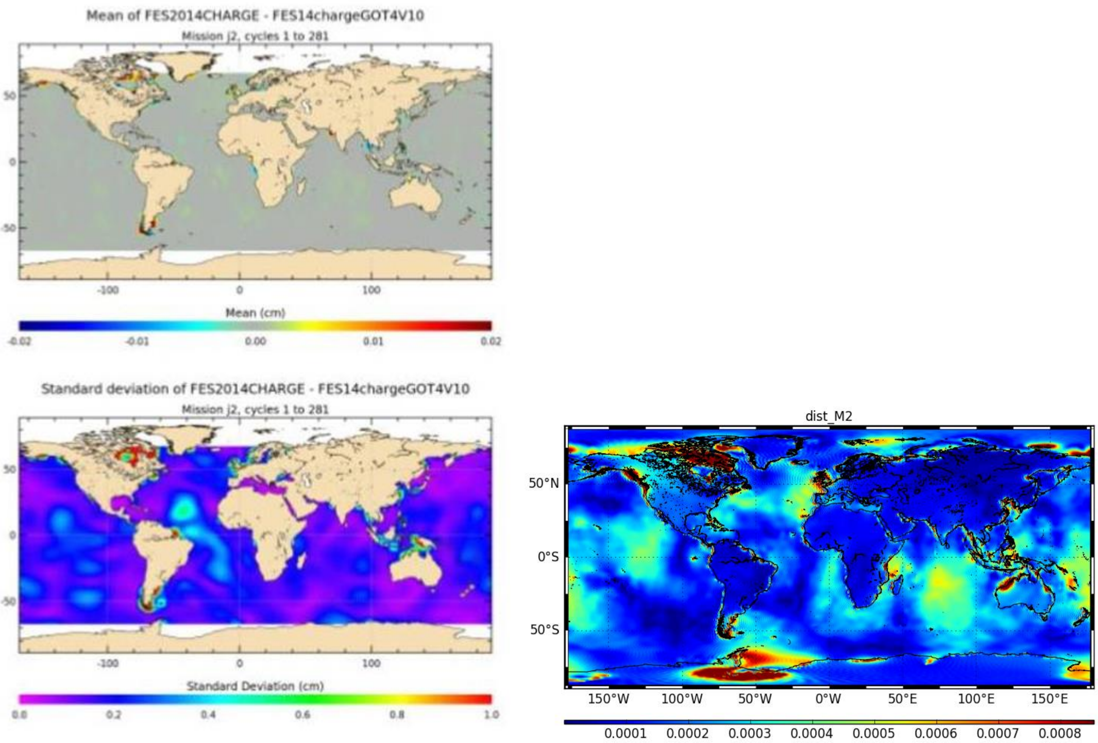


Figure 4: Mean differences between load tide FES2014 and GOT4V10 over ocean (top left) and its associated standard deviation (bottom left). Map of the M2 tide component over all surfaces (right).

An analysis over lakes was presented by Ritcher during a recent meeting (IUGG19-0380) [RD20]. He conducted an analysis of the lake tides and their comparison against modelling results in order to provide information on the tidal signal in nearby oceans and the elastic properties of the solid earth. He focused his work on the southern Patagonia and Tierra del Fuego, southernmost South America, where the interplay of tectonic processes and repeated glaciations has left behind a chain of large lakes aligned N-S along the eastern flank of the Patagonian Andes. Confined in between the Atlantic and Pacific oceans, this region is affected by large amplitude ocean tides along the Atlantic coast (which is indeed confirmed in the above map). Constraints on mechanical properties of the solid earth are of particular interest there for understanding the exceptional intensity of glacial-isostatic deformation observed at the Patagonian Icefields. Pressure tide gauge observations were carried out in Lago Argentino, Lago Viedma and Lago Fagnano. The lake tide signal is extracted from the lake-level records. **A maximum lake-tide amplitude of 5 mm is observed in Lago Fagnano for the M2 constituent only.** They have also computed the differences between their tidal loading model and a series of alternative predictions. They reveal mean RSS differences of **only 0.57 ±0.19 mm** in vertical deformation, for the predictions of the Ocean Tide Loading.

Table 1: Comparison of alternative predictions of tidal loading effects on vertical deformation with respect to the model. Deformation is given in mm.

ocean tide model		SEAT +		Ocean Tide Loading Provider							incl. local channels
		TPXO.7.2	EOT08a	EOT11a	EOT08a	OSU12	TPXO.7.2	FES2012	FES2004	DTU10	
	RSS	0.14	0.14	0.69	0.62	0.46	0.32	0.35	0.71	0.82	0.001
	min	−0.41	−0.35	−2.24	−2.00	−1.62	−1.21	−1.19	−1.85	−2.37	−0.020
	max	0.37	0.38	2.20	1.97	1.89	1.03	1.17	2.37	2.30	0.020
RMS	Q1	0.01	0.03	0.11	0.02	0.17	0.03	0.07	0.05	0.06	0.000
	O1	0.08	0.00	0.26	0.21	0.18	0.12	0.16	0.23	0.28	0.000
	P1	0.04	0.04	0.03	0.11	0.07	0.03	0.04	0.12	0.08	0.000
	K1	0.03	0.06	0.08	0.07	0.25	0.14	0.11	0.12	0.11	0.000
	N2	0.00	0.02	0.25	0.15	0.08	0.06	0.06	0.18	0.27	0.000
	M2	0.07	0.03	0.55	0.50	0.25	0.24	0.26	0.60	0.70	0.001
	S2	0.03	0.10	0.15	0.21	0.05	0.04	0.04	0.14	0.06	0.000
	K2	0.06	0.02	0.02	0.05	0.12	0.06	0.07	0.06	0.09	0.000
	M4	0.05	0.02	–	–	–	–	–	–	–	0.000

2.2.4 Satellite orbit determination

Using the metrics available on line and provided by the Copernicus CPOD service and the one presented during the last OSTST meeting in 2020 and shown in Figure 5, we can conclude that overall the radial performances of the Sentinel-3 orbits is below 1 cm without any significant geographical patterns observed so far (some geophysical patterns of the order of 2-3 mm at basin scale have been observed between DORIS and GNSS only orbit solutions computed by CNES, those very low geophysical patterns are not a concern for St3TART Hydro activities).

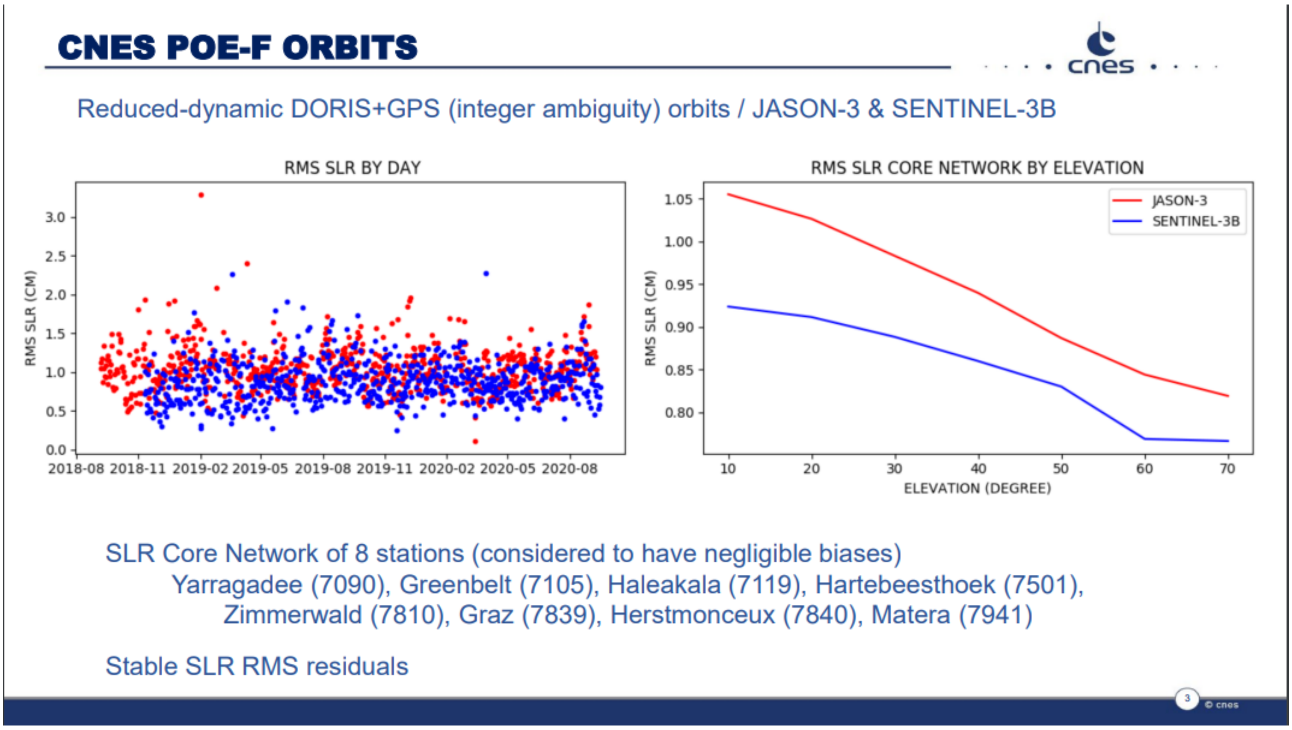


Figure 5: Results presented at the OSTST 2020 on the POE-F orbit performances

2.2.5 Ionosphere correction

Using the S3 MPC report [RD21], the JPL GIM based ionospheric correction proves to be accurate with a pretty good agreement with the altimeter dual frequency ionospheric correction (metric performed over the ocean). The ionospheric correction being not surface sensitive, we can safely use the metrics observed on ocean surfaces to derive metrics applicable to the inland surfaces. The Figure 6, extracted from the S3 MPC report (Figure 49 from the annual report) depicts the time average difference between the JPL GIM ionospheric correction and the S3A altimeter one. The mean difference is quite small, of the order of a few millimetres, mostly related to the Solar Activity.

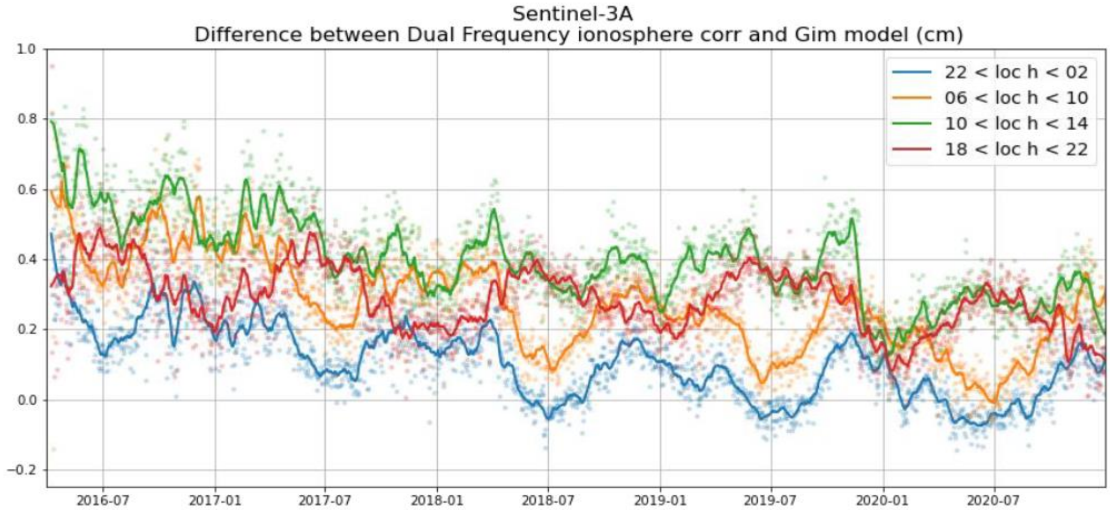


Figure 6: Time average difference between the JPL GIM ionospheric correction and the Sentinel-3A dual frequency ionospheric correction

Using the [Jason-3 annual report] [RD22], we can also see that the standard deviation is on average much below 1 cm as shown in Figure 7. We may also recall that S3A/B are sun synchronous missions with a local time of the nodes close to 10AM, 10PM which make them more favourable than the JA3/S6-MF missions (the errors are much larger around 2PM-5PM when the ionosphere signal reaches its maximum value).

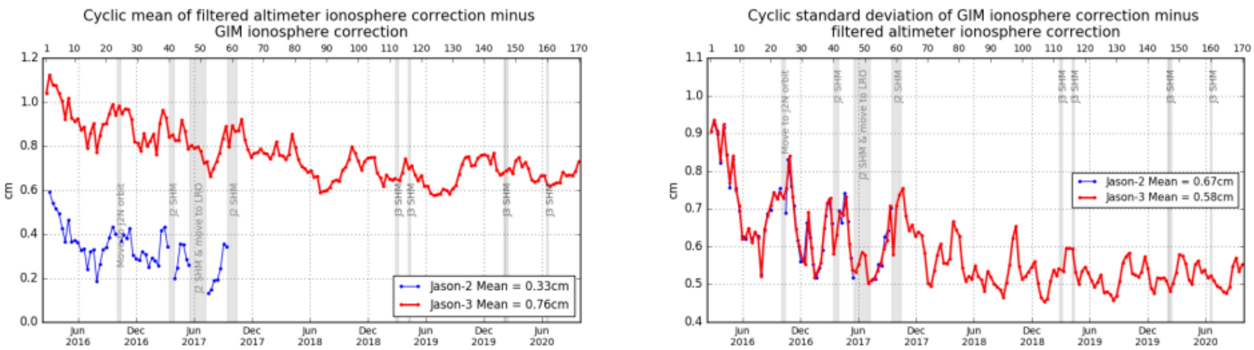


Figure 7: Cyclic mean (left) and standard deviation (right) of filtered altimeter ionosphere correction minus the GIM ionosphere correction

2.2.6 Dry troposphere correction

Based on the metrics provided by the Meteo France model we can state that the accuracy of the meteorological models is of the order of 1 hPa which translates in about 2 mm of Dry tropospheric correction. Another indirect analysis can be based on the use of the meteo models fields in GNSS data processing to correct for the atmospheric delay. For example, Lagler et al. [RD23], performed this analysis in their paper and using independent surface pressure sensors they reached the conclusion that the median of the global RMS is below 1.0 hPa and below 5 hPa for 95% of all stations (Figure 8).

Studies performed over the Lake Issykkul in the framework of Cal/Val of Jason-2, Jason-3, and Sentinel-3A&B have also explored the precision of corrections due to the dry troposphere [RD11] [RD24]. In situ atmospheric pressure from the lakeshore, over a decade of daily measurements have shown that once the dry tropospheric correction is done at a few kilometres from the lakeshore, the accuracy is about 4-5 mm. (figure below)

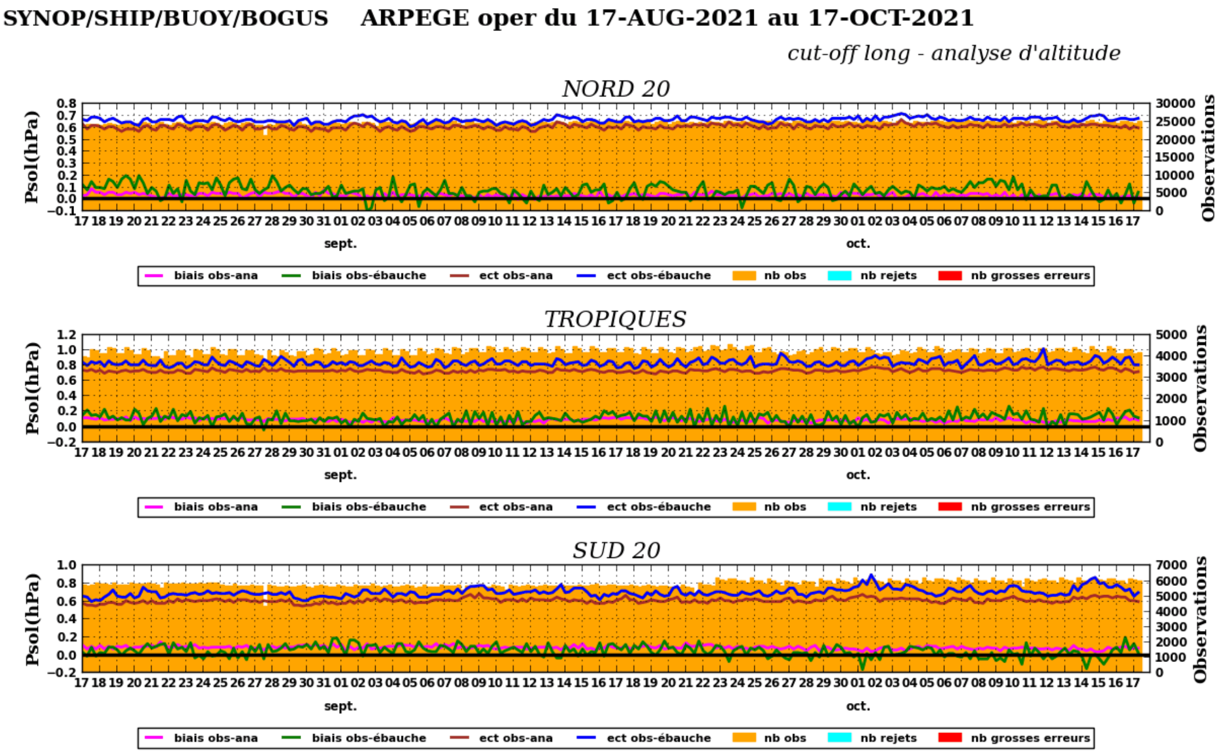


Figure 8: Differences between observations and meteorological models of dry troposphere correction

2.2.7 Wet tropospheric correction

Based on ECMWF models quality metrics available online on the ECMWF portal, the wet troposphere standard deviation is on the order of 1.5 cm on average (cf Figure 9 and Figure 10) with some expected geophysical patterns linked to the atmospheric patterns. This analysis is based on independent GNSS data (i.e., not used in ECMWF models) and provides a very good means to assess the overall quality of the ECMWF model which is used in all altimetric operational products.

Some specific analysis done over the lake Issykkul, with the help of a GNSS receiver, the wet tropospheric correction standard deviation achieved was 2-3 cm depending mostly on the period of the year (higher in summer than in winter).

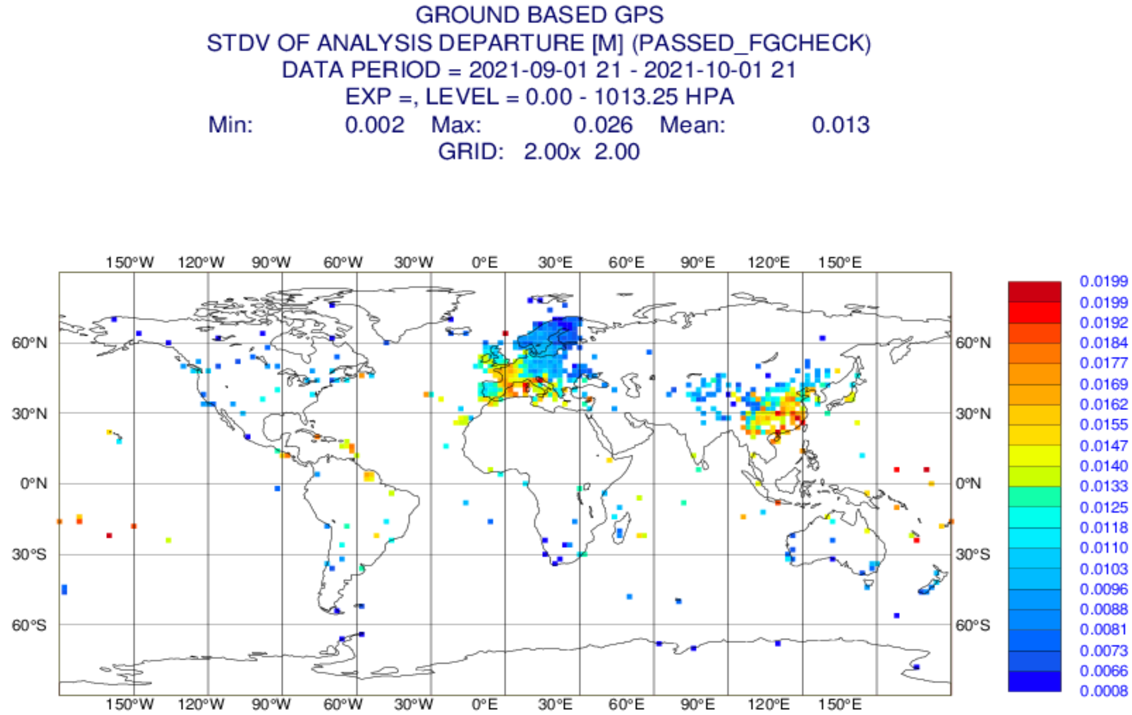


Figure 9: Map of the standard deviation of the difference between wet troposphere correction from the ECMWF model and computed from independent GNSS measurements

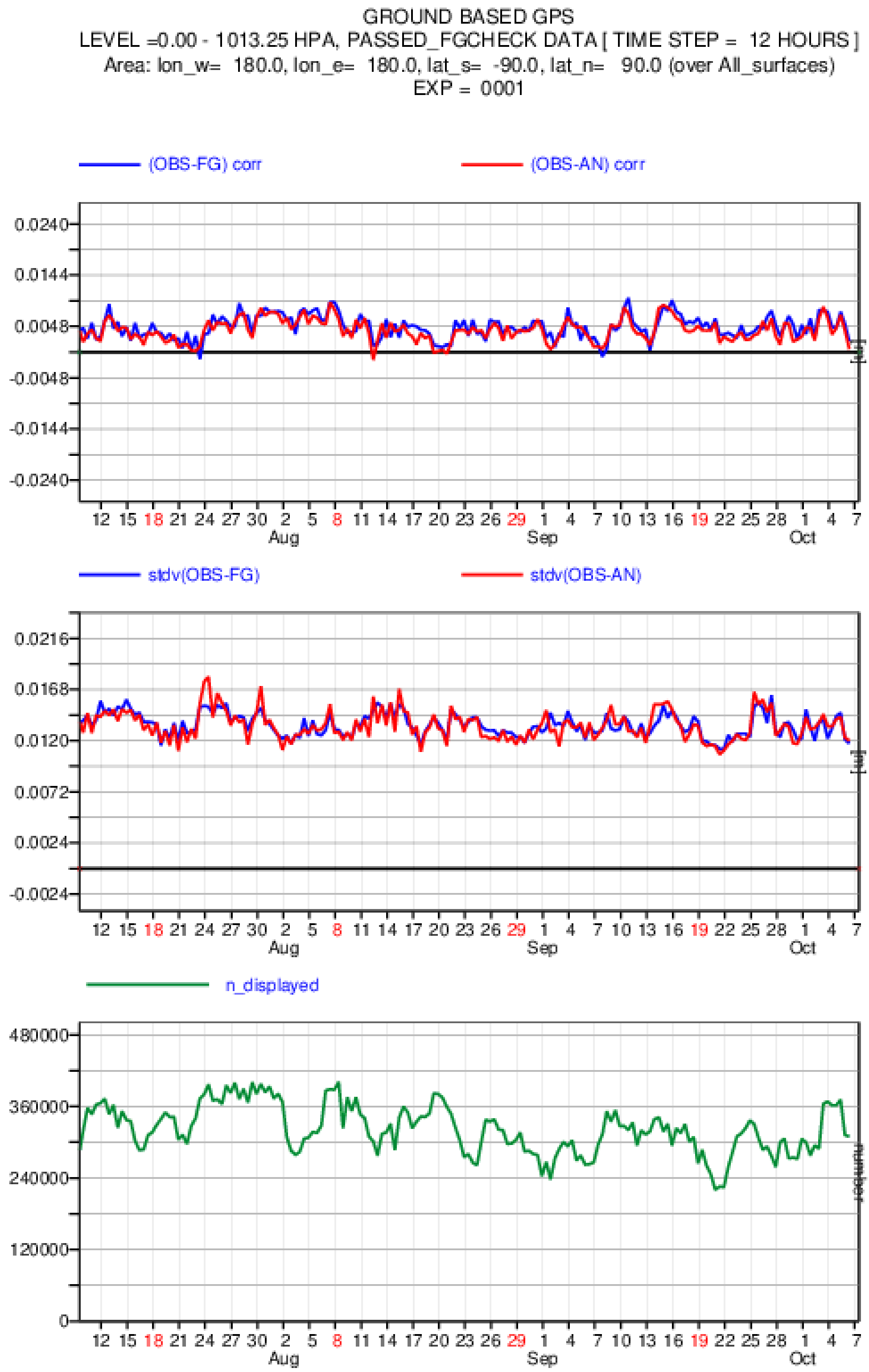


Figure 10: Comparison between wet troposphere correction from the ECMWF model and computed from independent GNSS measurements on the top plot, their associated standard deviation is shown in the middle figure and the number of observations at the bottom.

2.2.8 Ice period on high latitude water bodies

An ice climatology map has been computed by the SWOT PI team [RD62] and is depicted in Figure 11. This analysis is based on Landsat imagery and provides a very good means to identify the icy regions over inland water bodies. Not surprisingly, the Europe region is much more favourable compared to the other mid latitude zones. Performing the Cal/Val in Europe is thus considered a good choice for the North American Zone.

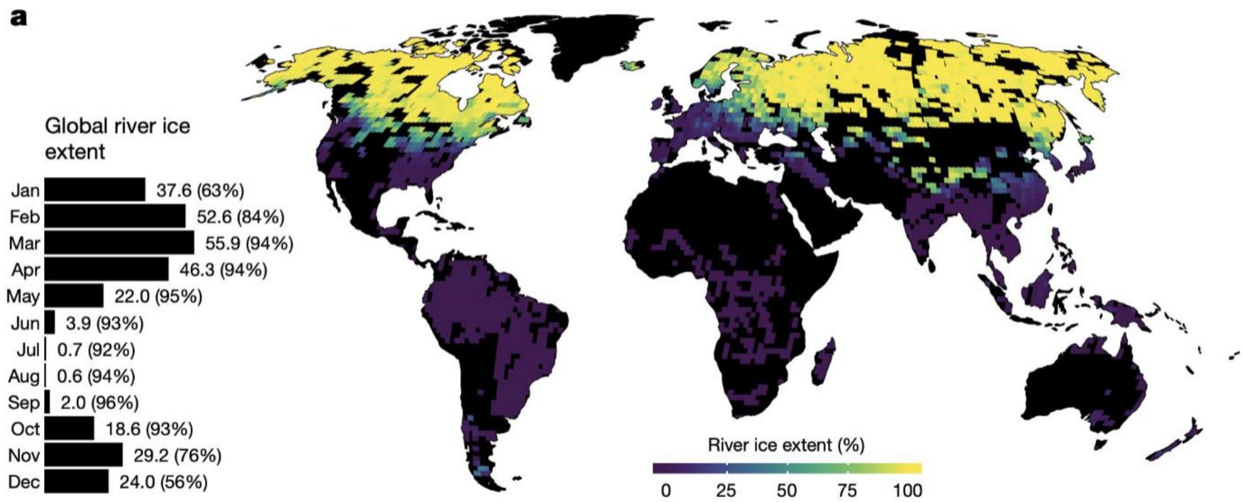


Figure 11: Climatological global river ice extent estimated from Landsat. The bar plot shows the monthly percentage of ice-covered rivers globally. The percentage of studied rivers observed successfully by Landsat is shown in parentheses.

2.2.9 Estuarine regions: ocean tide and dynamic atmospheric corrections signals

In estuarine regions, the river and ocean water masses meet, which results in a mix of various processes, such as river flow, ocean tide, storm surges and local sea level variations. The spatial scales of these processes are much smaller than the grids on which the ocean tide and the high-frequency dynamic atmospheric corrections are provided in the satellite altimetry products. For example, the two current reference tide models are provided on a 1/2° grid for GOT4.10 (i.e., about 50 km) and 1/16° grid for FES2014 (i.e., about 7.5 km). In addition, the interactions between the processes in estuaries result in non-linear signals and distortions in the water heights that cannot be corrected by simply subtracting the different components separately (ocean tide from one model + DAC from another model). In such a case, it is more appropriate to consider a high-resolution model solution (when available) that combines the various processes and tries to reproduce the local physics.

2.2.10 Derivation of the representative water surface height

So far various sources of uncertainty in deriving the altimetric height associated with every single measurement have been discussed. However, the challenge remains to nominate the representative height estimate over the water body of interest. Different data providers use different approaches in deriving altimetric height (Crétaux et al., 2011 [RD24]; Schwatke et al., 2015 [RD25]; Tourian et al., 2021 [RD26]).

As a practical solution, a virtual station is defined within which the representative water heights are sought. Finding the representative water height within a virtual station is an especially important aspect of data processing as it provides clarity regarding the validation assumptions and guarantees the reproducibility of results. The major challenges are:

- The **definition of the virtual station**

  The boundaries of a virtual station may be identified using shape files, geometric conventions, or visual inspection. One may further benefit from auxiliary sources of information, e.g., water occurrence frequency derived from imagery (e.g., Pekel et al. 2016 [RD27]), to filter out the effect of land contamination. The complexity in defining the virtual station may be case-dependent:

- Lake and reservoir: In case of highly varying surrounding topography, relying on shapefiles may lead to land contamination. Moreover, the existing islands within the lakes shall be excluded from the defined virtual station.
- River: In case of rivers, definition of virtual stations highly depends on river slope, channel geomorphology, altimetry crossing angle, and river width. We point out that currently available global water mask resolutions do not allow to cover all rivers. As an example, the Global Surface Water Explorer mask induces discontinuities in masks over rivers whose width is smaller than 60m.

- The **selection of the representative height**

  Depending on the defined virtual station and validation scheme, one may aim at selecting a single or multiple representative height(s) per satellite overpass. A single representative height is more likely to be desired over lakes or reservoirs. Finding a representative height over rivers becomes trickier as an estimation of the river slope is required for transferring all measurements to a specific location. In any case, the typical estimators are *median* and *mean*. One may as well rely on a single measurement, e.g., the most central measurement in the virtual station. It should be noted that an inevitable aspect of altimetric height estimation is the appearance of outliers despite addressing all possible caveats. This means that an outlier identification step is required prior to validation.

The above-mentioned complexities suggest that various realizations of height may exist for the same water body. A detailed documentation with respect to processing provides a basis for comparing different realizations and ultimately validating them.

2.2.11 Error budget of satellite altimetry over inland water bodies

The bibliography study performed here allows to summarize an error budget concerning satellite altimetry measurement over inland water bodies:

Table 2: Error budget of satellite altimetry over inland waters

Correction	Average order of STD	Reference in literature
Geoid height	Negligible impact if a sensor is +/- 1 km to the actual ground track	[RD12], [RD13], [RD14], [RD15], [RD16], [RD17], [RD52]
Pole tide, Solid Earth tide and Loading tide	Few millimetres	[RD18], [RD19], [RD20]
Orbit determination	< 1 cm	OSTST 2020, POE-F orbit performances [link]
Ionosphere correction from models	< 1 cm	[RD21], [RD22]
Dry tropospheric correction from models	< 1 cm	[RD11], [RD23], [RD24]
Wet tropospheric correction from models	~ 1.5 cm	ECMWF portal
Range estimation	Several centimetres or decimetres	[RD24], [RD25], [RD26], [RD27]

3 Calibration-Validation framework for inland waters

3.1 Calibration and Validation as a comparison process

Calibration and validation use other independent observations in comparison with measurements by the satellite altimeter in order to test the altimeter observations. Such comparisons can be made against observations by other satellites or observations from non-satellite methods (e.g., in situ, aircraft, drones, moored buoys). The results of such comparisons can be interpreted in three different ways:

a) A comparison can be used to validate that observation values are within an expected tolerance
b) A comparison can be used to evaluate the uncertainty associated with the satellite observation
c) A comparison can be used to validate independently determined uncertainties.

Traditionally, comparisons have been used for approach (a), i.e. to monitor whether satellite and reference measurements agree within the satellite's specified requirements. More recently, approach (b) or (c) has been attempted.

In a comparison, it is necessary to consider uncertainties associated with

1. The reference / compared observations
2. The satellite altimeter observations
3. The comparison process itself

Uncertainties associated with the comparison process itself include uncertainties related to the fact that the reference measurements and the satellite observations may be different, or uncertainties related to processing steps used to make the two measurements more equivalent (for example, by scaling or sampling observations to a common grid, or converting a radar freeboard into a lidar freeboard).

If the uncertainties associated with (1) the reference observations and (3) the comparison process themselves are much smaller than (2) uncertainties associated with the satellite altimeter observations, then the comparison can be used for approach (b), i.e., the comparison can be used to calculate/evaluate the uncertainty associated with the satellite measurements.

A metrological approach to comparisons would follow approach (c). That is, the three types of uncertainty associated with the two measurements (satellite and non-satellite) and the comparison process are independently evaluated and then the comparison is used to validate the uncertainties. It is for this reason, that the FRM needs an uncertainty evaluation independently determined and that we need to consider the uncertainty associated with the comparison process itself.

3.2 Calibration-Validation for inland waters

3.2.1 What comparisons can be performed

Figure 12 shows a schematic view of a generic validation scenario for satellite altimetry over inland water bodies. The dotted purple lines are the actual satellite tracks which deviate from the nominal track, the solid purple line. Every single dot represents one altimetry measurement of a specific sampling rate, hence assigned to geodetic and time coordinates.

The solid brown line delineates a virtual station. As visualised in the figure, the boundaries of the virtual station do not necessarily represent an ideally water-covered area or even an equipotential surface. The concept is however widely used to associate a single water level to a "virtual" station, the green marker. In this study, we may use the same delineation to simply limit the area over which validation is carried out.

The grey dashed line represents the trajectory of a moving platform. While the campaigns are designed to follow the nominal track, the actual moving sensor pass is almost always different from the nominal or any actual track.

A fixed in situ station (the grey square marker) is also depicted. As with most real situations, the fixed station is not located exactly over the nominal track or within the boundaries of the defined virtual station.

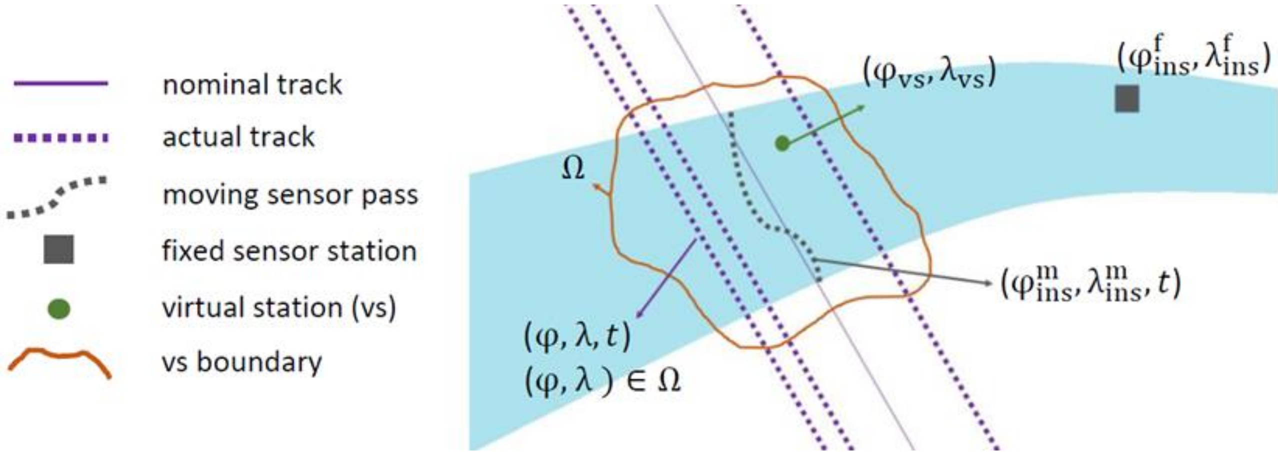


Figure 12: schematic view of a generic scenario for collecting satellite altimetry and in situ data over an inland water body

We aim at validating the water level derived from satellite altimetry over inland water bodies. Therefore, in its broad sense, our measurand would be 'altimetric water level'. However, a measurand needs to be defined in a precise manner. One way of identifying the acceptable measurands is to find multiple instances during data processing where validation can be performed. This concept is depicted in Figure 13. In this representation, the viable measurands are shown against dark grey background (see the legend), and each measurand is connected to one or more viable validation technique(s)[1].

This flowchart sets the focus on the waveforms as being the primary inputs of the analysis. The waveform is then retracked and corrected for different atmospheric and geophysical effects to output water level estimations of a specific sampling rate. Figure 13 shows the atmospheric (related to medium) corrections against orange background and the geophysical (related to target) corrections against blue background. The water level estimates are later averaged to represent the height of a virtual station. In this procedure, one may regard every measurand as a TDP, meaning that components of lower level, i.e., the inputs, would be regarded as an FDR. There are certainly some degrees of subjectivity in labelling intermediate inputs and outputs as TDPs and FDRs as every TDP would make an FDR higher in the processing chain and vice versa. Nevertheless, agreeing on these terms would help with the clarity of uncertainty analysis and the final documentation.

3.2.2 Comparison representativeness and uncertainty

Figure 13 also provides a full list of the available validation datasets, the FRMs. The collected in situ measurements are required to be fully characterized and traceable, meaning that their uncertainty is known. Despite the inland altimetry procedure for which a generic processing flow is perceivable, the validation instrumentation and techniques are diverse. Therefore, in this document, we only consider specific validation scenarios and derive the relevant diagrams and tables as an example.

[1] It is important to mention that the comparison diagram is meant to give a full overview of the discussed validation methods in St3TART project. One may argue that not all suggested validation datasets in Figure 13 fully comply with the definition of an FRM. Such argument however is out of the scope of the current document. Here, we are only interested in the systematic procedure through which a metrological uncertainty analysis is carried out.

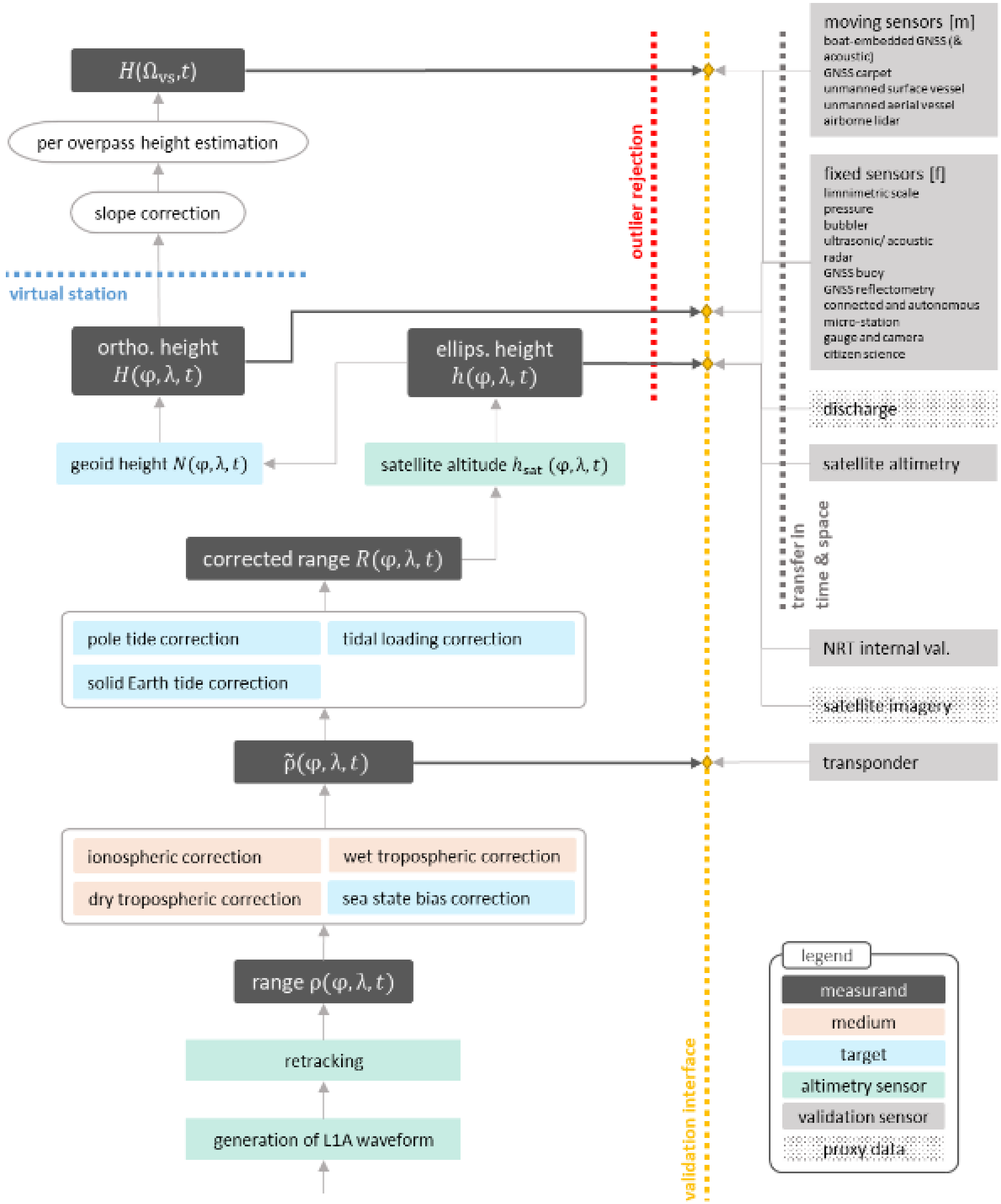


Figure 13: Comparison diagram – a conceptual representation of all validation scenarios

A major challenge about FRMs is that they are not directly comparable with TDPs. Generally, every set of in situ data should go through some post-processing procedure to ensure comparability with a specific measurand. A fully metrological analysis entails that this procedure is considered in the assessment of uncertainties.

It is important to notice that procedures required to ensure comparability do not have to be associated to FRM procedures necessarily. However, this association sets the ground for a more intuitive and generalized framework for validation purposes. To keep the clarity, hereafter we refer to the primary water level measurement of an in-situ station as the instantaneous measurement, h_{Inst} – e.g., the estimated water level using a micro-station. A number of procedures are then applied to the instantaneous height measurement to reach what can be referred to as the altimetry equivalent measurement, $h_{Alt\ Equiv}$ – e.g., the in-situ measurement that can be compared to the altimetry measurand. Figure 14 describes the required post-processing steps to transform the primary in situ measurement h_{Inst} into a quantity that can be directly compared to a measurand, $h_{Alt\ Equiv}$.

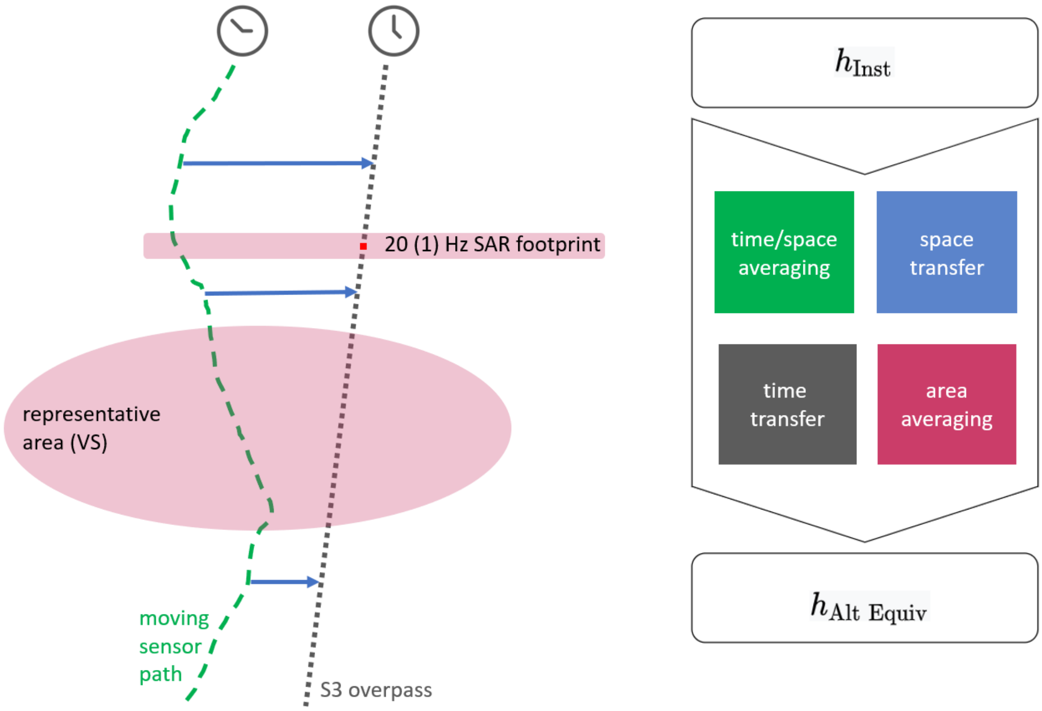


Figure 14: deriving altimetry equivalent height from the instantaneous height

- <u>time/space averaging</u>
  The primary in situ measurement of some instruments may be averaged over specific sampling intervals to generate in situ measurements of a lower sampling rate. This can be done to reduce the measurement noise or cancelling out the unwanted measurement effects imposed by the local topography. If applied, this step would be comparable to waveform multi-looking. While such averaging for a waveform leads to much complexity in deriving 'range uncertainty', in the case of in situ measurements, propagating the uncertainties due to some averaging is straightforward.

- <u>space transfer</u>
  In situ and satellite measurements are almost never perfectly collocated. Space transfer is the procedure to shift the in-situ measurements to where the satellite measurand(s) are located. If the area between the measurand and FRM data collection point(s) has been monitored with a sufficiently dense spatiotemporal sampling (either via satellites or in situ campaigns), the height difference can be modelled as a function of time and coordinates, and hence, corrected for. In practice, we would probably have access to the surface topography only as a function of location. It is quite often the case that we have no data at all to compensate for this effect. Expert judgment may therefore be required to quantify the uncertainty associated to the ignoring of the space transfer correction. When interpreting this step, there are a couple of remarks to be considered,
  - one, that even if we have enough data to establish a functional relationship for the height variation as a function of time and location, this function will suffer from some representation uncertainty. This is especially the case when we use archive data to model the surface topography of water bodies; and
  - two, that the location of altimetry samples is only an approximation of the true backscattering points within some effective footprints. Under favourable situations – e.g., no significantly high slope within the footprint – we may neglect the fact that the actual backscattering point is not known, and that the

relevant off-nadir correction is not applied. In unfavourable set-ups this may result in non-negligible rates of error in space transfer. In either case, the uncertainty associated to this effect needs to be quantified.

- time transfer
  In most situations, the in situ and satellite data are not collected concurrently. Even when they are, the temporal sampling is not necessarily the same. So, theoretically we need to transfer the in-situ time samples to that of the satellite measurement. It is important to notice that
  - where enough data is available, time transfer may be applied simultaneously with the space transfer. This is often not possible, and to apply time transfer separately can get far more complicated than applying the space transfer. Even if evaluating the height variation due to time differences is not possible, we still need to quantify some level of uncertainty as to not compensating for this effect.
  - Like the situation with space transfer, the temporal sampling of altimetry data is only an approximation of the time associated with the collection of a multi-looked waveform. This level of uncertainty is however negligible when trying to resample the FRM measurements.

- area averaging
  It is important to remember that validations are conducted in relation to a specific measurand. Hence, at the highest level of comparison, both TDPs and FRMs should present an identic measurand. In practice, reaching this identic measurand may be as simple as averaging satellite and in situ samples withing an area. However, in many cases there is a non-negligible representation error to this averaging since neither the satellite, nor the in-situ measurements represent the exact theoretical geometry of the preferred measurand. A good example here is the case of land ice altimetry. The multi-looked waveform over land ice would be affected by the topography within a specific footprint; the in-situ measurements are however collected within some contracted area which does not necessarily represent the bigger footprint, or worse, a much bigger virtual station.

Notice that the four FRM post-processing steps described above are note fully independent. In practice, applying some transfer function may compensate for more than one effect. What is important is to make sure that none of the points discussed by these steps are ignored while comparing FRMs to TDPs. There is also no order to applying any of the FRM post-processing steps. Depending on the validation circumstances, different orders may be preferred. It may, for instance, make sense to first apply the area averaging and then transfer FRMs to the location of TDPs.

4 Requirements for CAL/VAL altimetry measurements for hydrology

4.1 Focus on water surface height

Based on the uncertainty budget of satellite altimetry over inland waters described in 2.2.11, a specific focus must be put on the water surface height parameter for the FRM provision for Cal/Val activities.

The process of validation fundamentally involves a comparison of satellite altimetric heights with external height information. Therefore, one must take careful measures not to compare apples with oranges. Depending on the type of external height information a number of considerations are due.

1. **Geometric height.** The satellite altimetric observable is a geometric quantity, hence satellite altimetry basically provides ellipsoidal height. When an in-situ measurement is available close to the actual satellite track, the use of ellipsoidal height is recommended to avoid adding geoid errors into the Cal/Val uncertainty budget. This is the appropriate scenario for many validation sensors that are discussed in the next chapter, in which the height information is georeferenced through GNSS.
2. **Geoid model.** Subtracting a geoid model, which is by definition not error-free, from the heights would introduce geoid model errors into orthometric height. Note, however, that these geoid model errors are nullified if the same erroneous geoid model is used for both satellite altimetric heights and for the external heights. If different geoid models are used, e.g., a global model for satellite altimetry and a local model for in-situ stations, geoid model errors cannot be avoided.
3. **Physical heights.** If the external information for in-situ stations is obtained through national hydrological authorities, the height type should be ascertained. Many countries use orthometric heights (to be combined with a geoid), many other countries, e.g., France or Germany, make use of normal heights (to be combined with a quasi-geoid).
4. **Height reference system.** Satellite orbits are referenced in an international geocentric earth-fixed reference system, commonly ITRFxx (where xx denotes the particular realization of the frame). As a result, satellite altimetric ellipsoidal heights are provided in that system too. Removing a global geoid model, e.g. EGM2008, leads to global orthometric heights. National geodetic authorities or mapping agencies, in contrast, provide their national geo-referencing. For instance, European coordinate systems are commonly referenced in the European Terrestrial Reference System, most often in the realization ETRF89. The use of different geo-referencing in the validation process must be avoided by applying proper, and known, transformation beforehand.
5. **Time variability.** In situ stations may suffer from time-variable height effects for several reasons: tectonical motion, hydrological loading, temperature-dependencies (e.g., seasonal) of metal structures, ground deformation, erosion, etc. Many of these effects are below a threshold set by the inherent measurement accuracy of satellite altimetry. Although expensive, permanent, or epoch-wise GNSS monitoring would solve this problem. If that option does not exist, the potential maximum variation of height should be assessed.

4.2 Needs for Cal/Val over canals

Canals are very interesting for Cal/Val activities of satellite altimetry as they represent a simple case for evaluating the performances of altimetry over inland waters. Indeed, canals have the following valuable characteristics:

- Canals have a controlled water level which make it very predictive
- Canals are very calm which allow to avoid any surface roughness issues. The resulting radar echoes are very specular
- Almost no slope effect. It is thus easy to monitor with only one in-situ station
- Canals are easy sites to equip with in-situ stations and are most of the time well monitored with existing in-situ sensors.

In summary, small channels with favourable flyover geometry (e.g., when the satellite trajectory is perpendicular to the channel) are very good candidates for evaluating the maximum achievable performance of the altimeter.

In this frame, providing FRM over a canal is mandatory to evaluate the maximum achievable performance by a satellite.

4.3 Needs for Cal/Val over rivers

- Sensitivity to the surrounding terrain - radar echoes might be contaminated by human structures (in particular metallic ones), by land scattering, by other water surfaces nearby
- Sensitivity to the surface roughness (thus a wind sensor could be of interest)
- Sensitivity to the actual ground track location: +/-1 km is something that we do have to consider because of the topography: a single point wise information is not enough. We have to think in terms of river reaches and account for the river slope (and potential river falls: the large ones are well known but the small ones of the order of a few decimetres are generally not known). River slopes may also generate off-nadir observations that we need to take into account (decimetre-level impact).
- Sensitivity to the river slope that may change significantly depending on the season.
- Sensitivity to the river waves celerity
- For discharge computation and validation, permanent stations located under a bridge and providing actual water surface height + the surface velocity is a good solution (SWOT Discharge Group recommendation)

Based on these points here is a table summarizing the different needs for Cal/Val over rivers:

Table 3: List of the different needs for Cal/Val over rivers

Issue	Needs
Impact of the surrounding terrain	Cal/Val sites must be chosen without other strong radar scatterers in the surrounding area (metallic structures, other water surfaces in the radar footprint…). Waveform analysis allows to check this point.
Impact of the surface roughness	A wind sensor can be useful or an image of the water surface at the exact location and time of the satellite pass will allow to identify changes in surface roughness
Impact of the actual ground track location (movement of the ground track location)	1. Add constraints on the satellite orbit to limit the ground track excursion 2. The knowledge of the river slope within the satellite footprint (including the pass excursion) is mandatory
Impact of the river slope evolution with the season	The knowledge of the river slope as a function of the water height is mandatory
Discharge computation	A permanent station measuring water surface height and water surface velocity is mandatory

4.4 Needs for Cal/Val over lakes

- For small lakes:
  - Sensitivity to the surrounding terrain - radar echoes might be contaminated by man-made structures (especially metallic ones), by land scattering, by other water surfaces nearby.
  - Sensitivity to the actual ground track location: +/-1 km may generate off-nadir observations that we need to consider (decimetre impacts).
- For large lakes:
  - Sensitivity to the surface roughness: power return might not come from the nadir (thus a wind sensor could be of interest);

- Sensitivity to the surface roughness: in some cases, large SWH might be encountered over big lakes.
- Sensitivity to the geoid model errors if the in-situ means is not located under the actual ground track;
- Sensitivity to the actual ground track location: +/-1 km may generate off nadir observations that we need to consider (decimetres impacts).

Based on the points listed above, here is a table summarizing the different needs for Cal/Val over lakes:

Table 4: List of the different needs for Cal/Val over lakes

Issue	Needs
Impact of the surrounding terrain	Cal/Val sites must be chosen without any other strong scatterers in the surrounding area (metallic structures, other water surfaces in the radar footprint…). Waveform analysis allows to check this point.
Impact of the actual ground track location (movement of the ground track location)	Need an automatic check on the waveform to be sure that the altimeter measurements are on the targeted lake
Impact of the surface roughness	A wind sensor can be useful or an image of the water surface at the exact location and time of the satellite pass will allow to identify changes in surface roughness Physical retracker are mandatory to process the altimeter echo whatever the surface roughness
Impact on local geoid if the sensor is not located below the actual satellite pass	A precise knowledge of the geoid is mandatory. Periodic campaigns with moving sensors can mitigate this point
Impact of off-nadir detection	An accurate knowledge of the satellite measurement location is mandatory

4.5 Needs for estuaries

Estuaries are extremely dynamical regions in terms of water flux exchanges, and geomorphology and coastline changes. The interactions between the ocean tide flow, the storm surge, and the river flow can produce quick variations of several tens of centimetres in the water level, with typical non-linear distortions in the periodic tidal signal due to the river flow, upstream (Figure 15).

The implementation of Cal/Val sites for the SWOT mission, in particular in the Gironde and Seine estuaries that are strongly affected by ocean tides, have highlighted the need for very high time sampling in the in-situ measurements to be able to catch these quick variations. Typically, the comparisons (made by LEGOS, OBSPM and the University of Rouen) between gauge observations with 5-min time sampling and GNSS observations from the CalNaGeo carpet with 1-s time sampling have shown that the gauge can miss variations of more than 20 cm in the water heights in Rouen (Seine estuary). It is thus key to be able to measure the water height at high frequency at least at the time of the satellite pass.

Regarding the satellite altimetry observations, the presence of wetting/drying areas in the radar footprint, that may provide a strong backscattered signal at low tides (wet sand but no water), can affect the waveforms. The satellite measurements should be analysed to check the impact of such areas in the comparison with in-situ observations. The real location of the satellite measurement is also important in the presence of river branches, where the river water height can differ by several tens of centimetres.

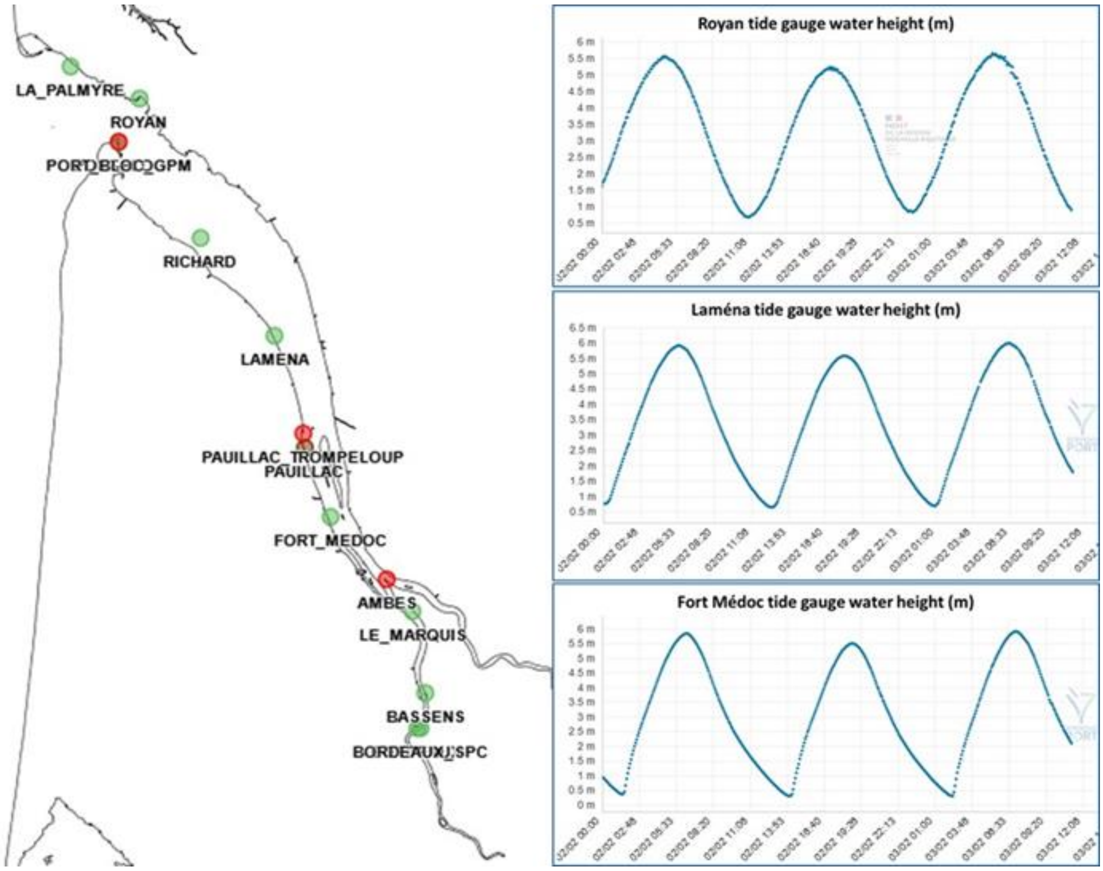


Figure 15: Water level (m) measured at three gauges in the Gironde estuary (data from the Vigicrues service). Note the distortion in the height at the gauges located upstream when the tide flows

In such dynamic environments, the ability to co-locate the altimetry and the FRM data, or to consider the impact of the distance between the ground station and the satellite track, is also a key aspect to perform relevant and accurate calibration and validation activities. Unlike river sections located far from the influence of the ocean, with seasonal variations of their slope mainly due to precipitation regimes, snow melting, and human activities such as irrigation, typical profiles of the river slope cannot be measured at seasonal scales in estuarine regions, where the slope changes all the time due to the ocean dynamics. This is the reason why the comparison between altimetry and in situ water heights in estuaries (Figure 16) shall dynamically consider the water height difference between the locations of the two measurements (ΔWSH in the equation below).

The field campaigns performed on SWOT estuarine Cal/Val sites (Gironde and Seine) with various instruments such as GNSS from the CalNaGeo carpet and Cyclopée instruments, drones and airborne LiDAR showed that, except for the aircraft, the other moving sensors are too slow to catch the water level dynamics over a few kilometres. On the other hand, the airborne LiDAR measurements are very expensive and can be limited due to weather conditions. In any case, using such instruments to systematically measure the river water height at each satellite pass is not an option, and high-resolution modelling is the most appropriate solution. Specific field campaigns can then be used to validate the model.

$$Diff_{WSH}(t,C) = WSH_{alti}(t,C) - WSH_{gauge}(t,G) + \Delta WSH[river, tides, surge](t,C,G)$$

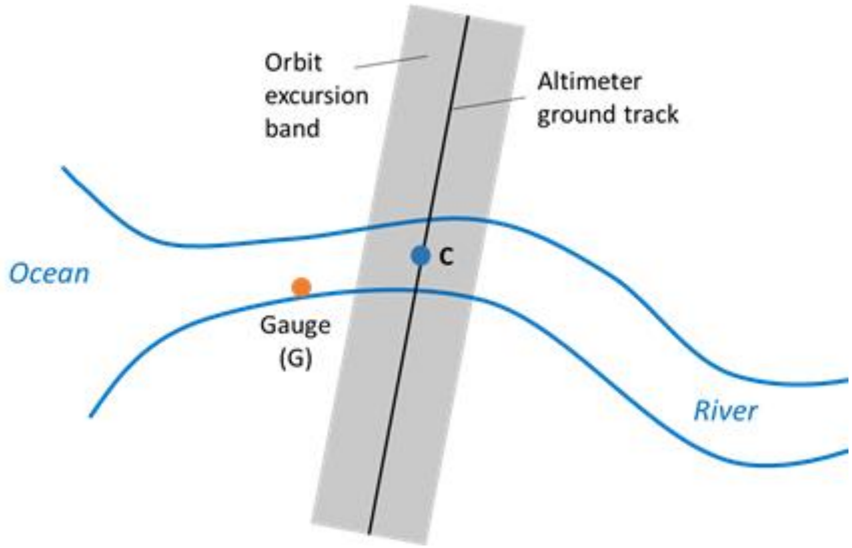


Figure 16: Diagram of the configuration for the comparison (at C point) between altimetry and FRM gauge data in an estuary region

The implementation of a high-resolution hydrodynamic model in an estuary is challenging because it requires highly accurate inputs to produce accurate simulations - each of these parameters (in addition to the model assumptions) contributing to the uncertainty budget of altimetry Cal/Val in estuarine areas:

- Well-defined coastline at the scale of the mesh grid (~ 20 m in the river)
- Accurate bathymetry at the scale of the mesh grid (<= 100 m) with a known vertical reference
- Geoid information (with known vertical reference) to be used as vertical reference for the bathymetry in the river (the model reference is the mean sea level in the ocean)
- Gauges (with known vertical reference) for upstream boundary conditions, assimilation or validation
- Water elevations from another hydrodynamic model for tide and surge in the ocean, at the open boundary.

The implementation of hydrodynamic models in estuaries such as the Gironde, the Seine (Figure 17) and the Elbe (work performed by LEGOS, University of Rouen and NOVELTIS) has highlighted the difficulty to access the needed inputs or associated information such as vertical references. For instance, the bathymetry information in the ocean part and in the river part can be distributed by different institutes (hydrographic services, harbours) with different references and/or different processing strategies that can create jumps at the junction of the datasets, and produce perturbations in the model. Up-to-date coastlines are also sometimes difficult to access, as estuarine regions can strongly change within a few years, due to geomorphology changes and to new constructions and port infrastructures. Sentinel-2 optical images can be used to detect the waterlines, but they can be strongly affected by the cloud cover, and generally do not correspond to the real coastline (at very high tide) due to the sun-synchronous nature of this satellite (same S2 tide at each pass). The Sentinel-2 waterlines can also be used to validate the location, the extent, and the timing of the wetting and drying areas in the hydrodynamic simulations.

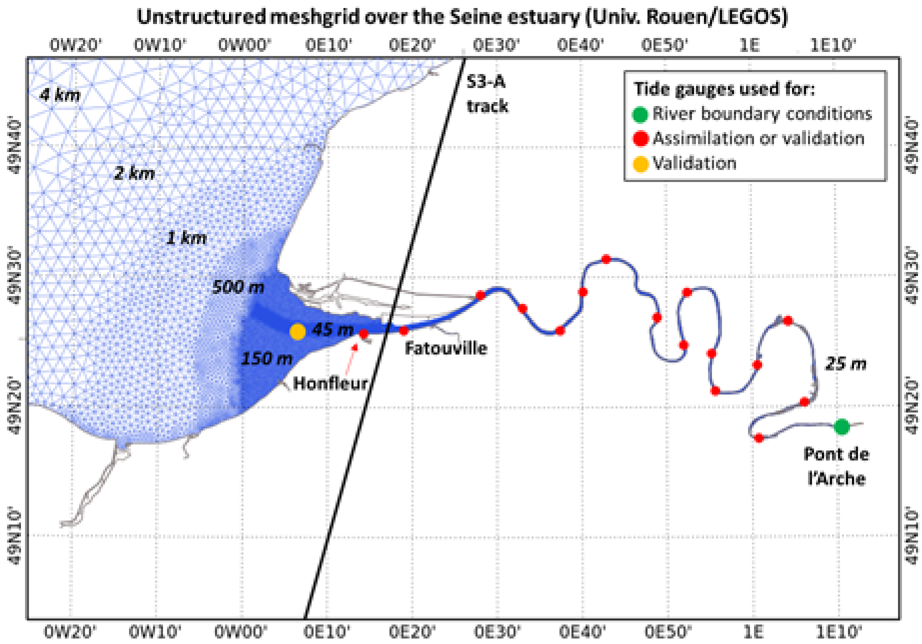


Figure 17: Configuration of the hydrodynamic model on the Seine Cal/Val site

The existing gauge networks can be used to prescribe the upstream boundary conditions of water elevation to the model, and to validate the simulations. They can also be used to constrain the model through data assimilation. If the vertical reference of the gauges is unknown, which often happens because these instruments are generally used to monitor water level variations instead of absolute levels, field campaigns with GNSS instruments such as the CalNaGeo carpet or Cyclopee can be performed to measure the river water height close to the gauge instruments, as it was already done in the Gironde and Seine estuaries for the SWOT Cal/Val sites. However, the existing gauge networks are often based on instruments of different types, different generations, and different levels of accuracy, which must be taken into account in the comparison with the model or in the data assimilation process. Also, to produce hydrodynamic simulations at any altimeter pass, the gauge time series used as upstream boundary condition needs to be as complete as possible (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 different aspects, the implementation of Cal/Val sites in estuaries is challenging and is still in the preliminary phase. The analyses of the Sentinel-3A data in Honfleur, as well as the SWOT data on the Gironde, the Seine, the Elbe, the Severn, the Maroni, the Mississippi, the Saint-Laurent, etc., will bring new insight and will help further define such Cal/Val sites in the coming months.

5 Means for CAL/VAL activities

This chapter is dedicated to perform a full review of all the sensors that have been used for many years for Cal/Val activities for inland waters, but also to review all innovative sensors that can fulfil the needs and potentially be used in the frame of the St3TART project.

5.1 Standard sensor sheets

In order to list and compare all sensors that can be used to perform water surface height measurements, we define a "standard sensor sheet" that will ease the review of the different means for both permanent and periodic campaigns. The standard sensor is presented below. This table is filled with the information provided by the suppliers but also with information and metrics based on the use of those sensors during previous campaigns. All the sensor sheets are provided in the appendix of this document.

Table 5: Example of empty standard sensor sheet used to characterise all sensor means in the St3TART project

	Main measurement	Extra measurement
Sensor Name		
Sensor Type		
Measurement type		
Wavelength		
Measurand		
S.I.		
Precision		
Accuracy		
Uncertainty		
Measurement drift		
Measuring range		
Measurement frequency		
Acquisition rhythm		
Transmission delay		
Calibration Method		
Deployment method		
Deployment constraints		
Needs of external data		
Dimensions		
Weight		
Power supply		
Autonomy		
Expected lifetime		
Data transmission		
Data Storage		
Maintenance		
Need for human intervention		
Company		
Price		

5.2 Existing sensors

In this part, we provide a list of sensors that have been widely used since the beginning of Cal/Val activities for inland water. Their associated sensor standard sheet (plain rules, pressure transducer, …) is given in the appendix of this document.

We decided to present a list of sensors dedicated to the water height monitoring, classified according to the different uses:

- **Fixed sensors:** instruments to be fixed on a bridge, a peer, rocks, pole or any kind of structure at a fixed location
- **Moving sensors:** instruments able to be used on moving platforms (drones, boats, cars, etc...)

5.2.1 Fixed sensors

5.2.1.1 Limnimetric gauges

Description: The classic gauges are limnimetric rulers that are installed in the water with an emerging part so that a person can read the level on it. The gauge has a scale to read the level to the nearest centimetre. Classic limnimetric gauges are widely used in national in situ station networks.

Figure 18: Example of a limnimetric gauge installed on a bridge pier

Measurement principle: The measurement principle is very simple; a person comes to the location of the gauge and reads the level on it. The water level is read on the rule and is given with respect to the zero of the scale.

Implementation: Most of the time, limnimetric gauges are fixed on a solid structure (a wall, a bridge pier, etc...) inside the water body. During the installation, it must be ensured that the gauge has always a part into the water and an emerging part. The gauge must be long enough to account for the water level variability. When no solid structure is available, the steps must be anchored into the margin and levelled one to each other.

Calibration: Reading the water level on the gauge provides a relative measurement with respect to the zero of the scale. The zero of the scale must be calibrated and levelled (orthometric height) using GNSS measurement to obtain an absolute water surface height. The best way to ensure calibration is to build a reference point ("e.g. NGF IGN 69 in France") near to the station: as this reference point will be considered fixed (anchored in the mother stone), the gauge is more easily levelled in comparison to this point.

Performances: Limnimetric gauges have demonstrated their capability to provide water surface height with a centimetre-level accuracy after GNSS positioning and levelling (Calmant et al. 2013 [RD39])

Strengths: Limnimetric scales are cheap to buy and require a very low maintenance level. The installation does not require power supply or any connectivity wire.

Drawbacks: The installation requires a solid structure to be fixed on, or concrete execution for margin anchoring. An easy access to the water body is mandatory to install the gauge. In order to sample the low levels, the gauge must be installed during very low waters. A person must be present at the gauge location to read the level (no automated data transmission).

5.2.1.2 Pressure sensors

Description: Based on a Quartz (0,01 FS) or a Piezometric sensor (0,2 FS), these instruments must be immersed. The price is depending on the accuracy of the sensor: a few thousand euros for Piezometric sensors to ~15 k€ for Quartz sensors. This kind of sensor is largely used in national networks such as Vigicrues in France.

Figure 19: Illustration of pressure sensors

Measurement principle: The sensor measures the pressure of the water column above it. The sensor provides a relative water height as the measurement is the height of the water column.

Implementation: The sensor must be fixed on an underwater rigid structure. The sensor must not move. The sensor positioning (and its orthometric height) must be precisely measured using a GNSS sensor to provide the absolute water surface height. A Power supply and a transmission system must be added to the installation.

Calibration: A GNSS calibration of the sensor (GNSS positioning of the sensor and of the water surface) is needed to provide orthometric height of the water surface. Then GNSS calibration are regularly mandatory since the sensor are impacted by drifts due to ageing and temperature sensitivity (Sorensen & Butcher 2011 [RD40])

Performances: Pressure sensors provide measurements of the height of the water column with a centimetre-level accuracy (usually expressed in % of the full scale -FS-, the total water column for which the sensor is designed). However, pressure sensors are impacted by drift due to the instrument ageing and the water temperature sensitivity (Sorensen & Butcher 2011 [RD40]) that can reach up to 27 mm in 100 days.

Strengths: Pressure sensors provide a good accuracy and measure the height of the water column. Pressure sensors are also affordable to purchase and easy to set-up.

Drawbacks: As pressure sensors must be immersed, these sensors can be damaged during flood events. The installation requires access to the river bottom and a solid structure to be fixed on. Regular calibrations are mandatory to correct from the non-negligible sensor drift. A Power supply and a transmission system must be added to the installation and must be installed out of the water. A cable must connect the sensor (installed into the water) with the power supply and connectivity system (out of the water).

5.2.1.3 Bubbler sensors

Description: The Bubbler sensor uses a pressure transmitter technology. This kind of sensor is widely used in different countries around the world (French network, German network, Italian network, etc...).

Figure 20: Example of bubbler sensor installed on a river bank

Measurement principle: A bubble sensor measures water level based on the amount of pressure it takes to push an air bubble out of an orifice line (plastic tubing) and into the water body. This pressure, often referred to as the “line pressure”, requires changes with the elevation of the water. As the water elevation rises and falls, so does the line pressure needed to discharge bubbles. The line pressure value, measured in psi, is then converted into the desired units of measurement to represent water level from the point of discharge to the water’s surface.

Implementation: The sensor must be fixed on an underwater rigid structure. The sensor must not move. The sensor positioning (and its orthometric height) must be precisely measured using a GNSS sensor to provide the absolute water surface height. A Power supply and a transmission system must be added to the installation. A hose is also required for this kind of sensor.

Calibration: A GNSS calibration of the sensor (GNSS positioning of the sensor and of the water surface) is needed to provide orthometric height of the water surface.

Performances: Bubbler sensors provide measurements of the height of the water column with a sub-centimetre-level accuracy.

Strengths: Bubbler sensors provide a good accuracy and measure the height of the water column. Bubbler sensors are also affordable to purchase.

Drawbacks: As Bubbler sensors must be immersed, these sensors can be damaged during flood events. The installation requires access to the river bottom and a solid structure to be fixed on, especially concerning the hose. A Power supply and a transmission system must be added to the installation and must be installed out of the water. A cable must connect the sensor (installed into the water) with the power supply and connectivity system (out of the water).

5.2.1.4 Ultrasonic / Acoustic sensors

Description: In operation, the sensor is mounted over the water. To determine the distance to the water, it transmits a sound pulse that reflects from the surface of the water and measures the time it takes for the echo to return.

Figure 21: Example of an ultrasonic sensor installed above a canal

Measurement principle: Ultrasonic sensors use the speed of sound to measure the time taken for an ultrasonic pulse to travel from the sensor to the fluid level and back to the sensor. They provide fast, non-contact measurements at distances up to 50 feet (15.2 metres). The sensor measures the air distance between the water surface level and the sensor itself.

Implementation: The installation on the field requires a structure allowing the Ultrasonic sensor to have a vertical looking to the river. This structure can be a bridge, a peer, a pole above the water. The distance between the water surface and the sensors must be lower than the maximum measurement range. Power supply and connectivity must be brought to the sensor through cables as the sensor is provided without any power supply system or data transmission system.

Calibration: A GNSS calibration of the sensor (GNSS positioning of the sensor and of the water surface) is needed to provide orthometric height of the water surface.

Performances: The accuracy is better than 0.5% of range at constant temperature, but is affected by temperature gradients, target echo strength, and speed of sound in vapours.

Strengths: Sensor is not in contact with water which facilitates the installation and makes it safe from the impact of a flood event. Ultrasonic sensors provide good accuracy. Ultrasonic sensors are affordable.

Drawbacks: The ultrasonic sensor needs to be installed on a fixed structure. The sensor must have a nadir point of view above the water surface. Power supply and connectivity are needed.

As the air temperature changes, the speed of sound changes, by 0.17% per degree Kelvin. Unless the sensor can compensate for this change of temperature, then as the temperature varies, so will the accuracy of the sensor. Although many of the manufacturers claim to be compensating for fluctuations in the temperature, Heiner et al. (2012) [RD41] noticed that during rapid changes in temperature, some of the sensors that “compensate” for temperature fluctuations would not provide repeatable calibrations.

5.2.1.5 Radar sensors

Description: Radar water level sensors are designed to measure the air distance between the sensor and the water level. This remote sensing sensor is positioned above the water with a vertical point of view. The radar is equipped with an antenna or a horn. Radar sensors are widely used in the different national networks around the world.

Figure 22: Example of a radar sensor installed above a river

Measurement principle: The operation of the equipment is based on the emission of a continuous radar signal through its antenna. The signal sent is reflected by the product and captured in the form of an echo by the antenna. The frequency difference between the signal sent and the received signal is proportional to the distance and thus to the filling height. The filling height determined in this way is transformed into a corresponding output signal and output as a measurement value.

Implementation: The installation on the field requires a structure allowing the Radar sensor to have a vertical looking to the river. This structure can be a bridge, a peer, a pole above the water. The distance between the water surface and the sensor must be lower than the maximum measurement range. Power supply and connectivity must be brought to the sensor through cables as the sensor is provided without any power supply system or data transmission system.

Calibration: A GNSS calibration of the sensor (GNSS positioning of the sensor and of the water surface) is needed to provide orthometric height of the water surface.

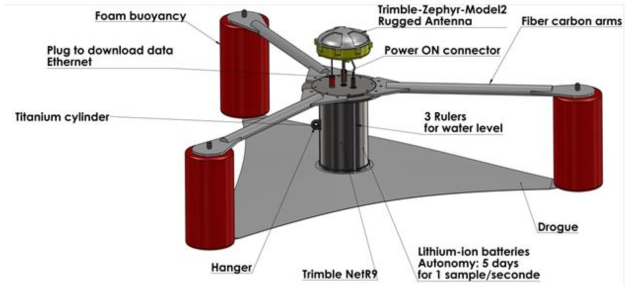
Performances: The accuracy is about ±0.1 % full scale. The sensor is sensitive to temperature variations but includes a temperature sensor for the compensation.

Strengths: The sensor is not in contact with water which facilitates the installation (even if power supply and connectivity must be added) and makes it safe from the impact of a flood event. Radar sensors provide good accuracy.

Drawbacks: The radar sensor needs to be installed on a fixed structure. The sensor must have a nadir point of view above the water surface. Power supply and connectivity must be added. Radar sensors are not lightweight.

5.2.1.6 GNSS buoy

Description: The sensor is based on a GNSS receiver packed in a container and in a buoy with batteries and the antenna. It's a Dual band and a multi-constellation receiver (L1, L2) for good accuracy. A reference station can be located at less than 10 km otherwise a PPP processing is used.



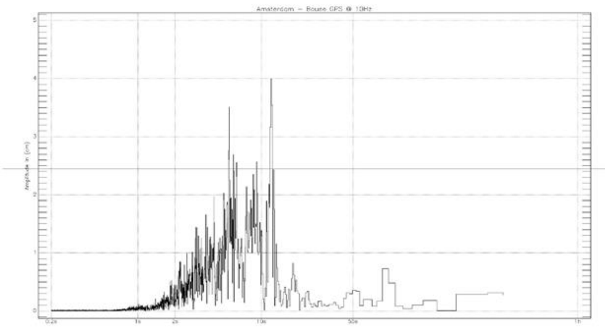


Figure 23: Picture of a GNSS buoy (top left), scheme of a GNSS buoy (top right) and GNSS buoy spectrum at 10Hz on Amsterdam island with wave signal between 2 and 12 seconds (bottom left)

Measurement principle: The antenna height is measured from its reference down to the water surface using GNSS receiver signals. Need post calculation (for high precision).

Implementation: The buoy is installed in the water and is fixed at the bottom of the water body to prevent any drift in its location. If installed in rivers, the current needs to be low. A transmission system must be added to send GNSS raw data

Calibration: Another GNSS receiver can be used to check the water level given by the GNSS buoy. Concerning the positioning processing, a reference GNSS receiver can be used to use RTK or PPK algorithms. If it is not the case, a PPP algorithm is used.

Performances: The performances are related to the GNSS processing. The centimetre-level accuracy is obtained through RTK, PPK or PPP processing.

Strengths: The buoy directly includes a GNSS receiver which eases the calibration. Very good accuracy and no drift of the sensor. The GNSS also provides in-situ information on troposphere corrections.

Drawbacks: The access to the water must be possible to install the GNSS buoy. A fastening system must be used to secure the buoy and prevent any location drift.

5.2.1.7 GNSS sensors with reflectometry (GNSS-R)

Description: GNSS reflectometry is passive sensing that takes advantage of and relies on separate active sources - the satellites generating the navigation signals. GNSS-R is simply done by installing a specific GNSS receiver with 1 or 2 antennas. The antenna must be installed several metres above the water surface.

Measurement principle: The measurement principle is based on the interference between GNSS signals coming directly from GNSS satellites and from the GNSS signals reflected by the water surface. The reflected signal will therefore interfere with the direct signal at the antenna and affect the measurements made by the receiver. These so called multi path interferences have a negative effect on the measurements carried out for positioning, and are generally sought to be removed in classical geodesy. In GNSS reflectometry, on the contrary, the analysis of these interference will provide useful information about the reflected signal, and therefore about the characteristics of the reflection surface. Lan Vu 2019 [RD43] explained that altimetry measurements are made by estimating the delay between direct and reflected signals and can reach an accuracy to the centimetre level.

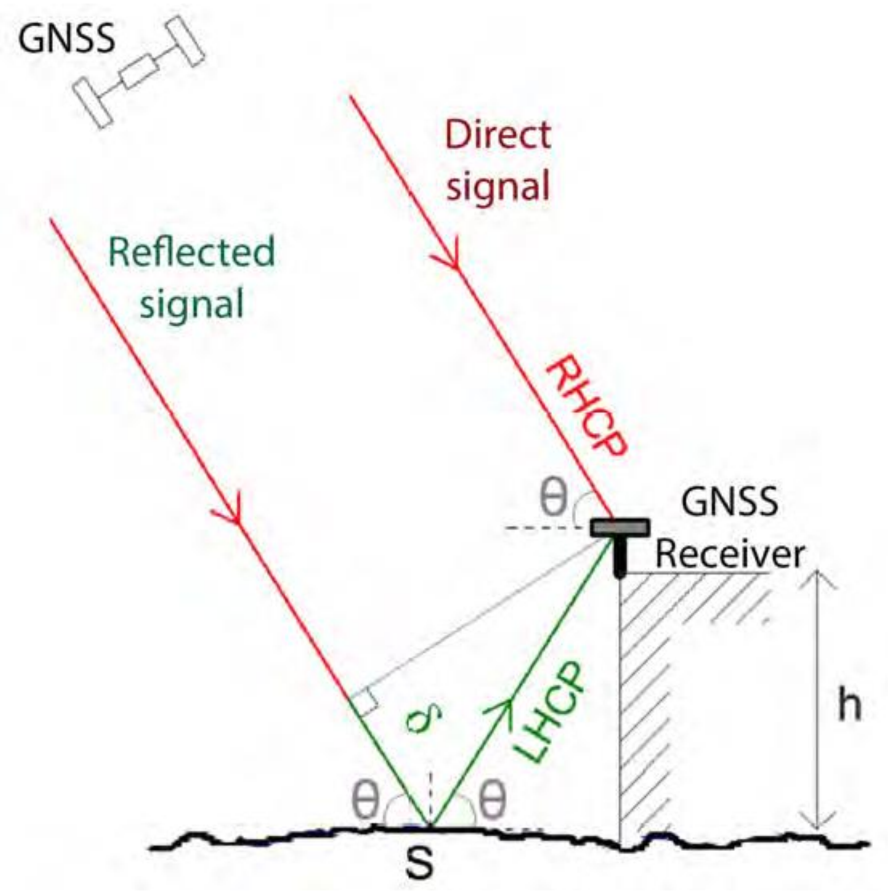


Figure 24: Measurement principle of GNSS-R system

Implementation: A GNSS receiver and its antenna must be positioned several metres above the water surface on a static structure. The structure can be located above the water (bridge) or on the river/lake banks. Power supply and data transmission must be added.

Calibration: Another GNSS receiver can be used to check the water level with classical GNSS positioning algorithms

Performances: Lan Vu 2019 [RD42] has demonstrated an accuracy of about ~10 cm.

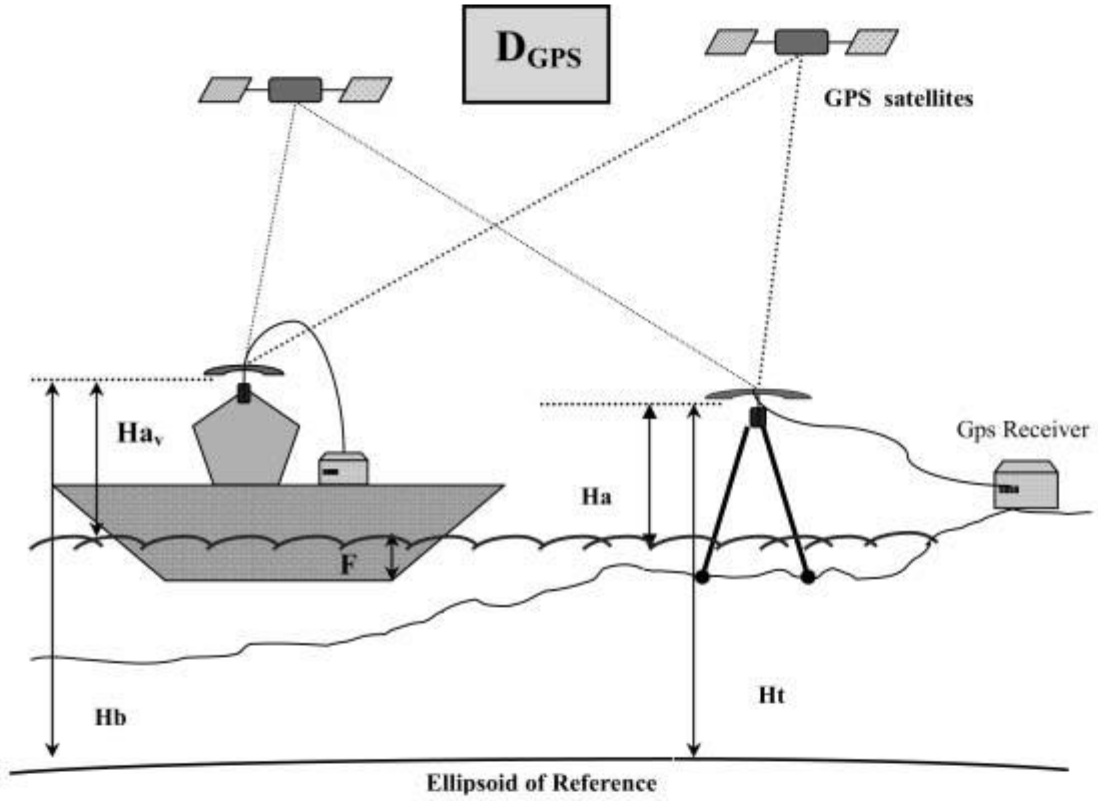
Strengths: The installation is simple; the only requirement is a static structure at several metres high above the water level to install the GNSS antenna. The main advantage of GNSS-R is the absolute geo-referencing of the in-situ station through the direct signal, 1) making the GNSS-R-derived heights immediately comparable to satellite altimetry, and 2) monitoring potential vertical deformations with the same system.

Drawbacks: The GNSS receiver and antenna are not affordable. The accuracy of 10 cm can be a limitation.

5.2.2 Moving sensors

5.2.2.1 Boat-embedded GNSS sensors

Description: The GNSS sensor on a boat consists in mounting a GNSS receiver and its antenna on a boat navigating on a water body. This solution has been used many times by Crétaux et al. 2011 [RD24] on the Issykkul Lake.



Ha_v, Ha : Antenna height above the lake (vessel land fixed points respectively)
Hb, ht : Vertical position of GPS antennas above the ellipsoid of reference (vessel, and land fixed point respectively)
F : floatability of the vessel (depends on velocity)
D_{GPS}: differential GPS point positioning

Figure 25: Measurement principle of the boat-embedded GNSS sensor

Measurement principle: The principle is based on GNSS processing (RTK, PPK or PPP) performed on GNSS measurement done by the receiver on-board the boat. The height of the antenna above the water surface has been measured beforehand. Another GNSS receiver (the base) is installed on the banks and is used to perform the PPK or RTK processing.

Implementation: The implementation required to have easy access to the water body in order to launch a boat. The water body must be navigable. The antenna height above the water must be measured beforehand.

Calibration: The second GNSS receiver is used to measure the water surface height close to the banks. This measurement is used to calibrate the water surface height measurements made by the GNSS receiver on-board the boat.

Performances: An accuracy of 3 to 4 cm has been reached by Crétaux et al. 2011 [RD24]. A strong sensitivity to the boat speed has been demonstrated in this paper but a correction has been computed and applied.

Strengths: Solution directly based on GNSS measurements which are easy to implement. This solution makes it possible to measure long distances, provided that the water body is navigable.

Drawbacks: The water body must be easy to access in order to launch a boat. The water body has to be navigable. The determination of the height of the antenna above the water is a strong contributor to the uncertainty and evolves with the boat velocity.

5.3 Innovative sensors

We list and briefly describe in this part the innovative sensors that have been recently developed and used or could be used in the frame of Cal/Val activities of altimetry measurements on inland water.

5.3.1 Fixed sensors

5.3.1.1 Autonomous and connected station

Description: Developed by vorteX.io, this innovative system may be used for both systematic and periodic field campaigns. It is based on a smart, compact & innovative remote sensing instrument combining a LiDAR and an infrared camera to provide water surface height with the associated standard deviation, LiDAR amplitude and images of the water surface, even by night. Thanks to the camera, the Micro-Station also provides water surface speed estimates. The system is fully automatic and connected using either GSM or IoT approaches (ongoing development based on Kineis space IoT system). Each time measurements are transmitted by the station, a complete house-keeping telemetry (battery level, connectivity level, power provided by the solar panel, voltage and amperes of the different sensors and electronic cards, etc.) is also sent in order to perform a complete real-time health check of the station. This feature allows remote maintenance and thus to intervene on the field only when a hardware problem has been diagnosed, which dramatically lowers maintenance costs.

Figure 26: Picture of a vorteX.io micro-station installed on the Hers River in Mazères (South of France)

Measurement principle: Measurements are inspired by satellite altimetry and use a specific LiDAR and an infrared camera. The LiDAR emits an infrared pulse (850 nm) and the LiDAR waveform is processed on board the station to measure the range distance between the micro-station and the water surface. Then the reference altitude measured by a precise GNSS measurement is applied to the measurement in order to provide water surface height with respect to the local geoid or the reference ellipsoid. The LiDAR works at 7Hz, and the water surface height provided and transmitted by the instrument is the median on a 30 second duration (the duration is remotely controlled, and can be remotely changed). All measurements are transmitted in real time

The on-board camera is used for different purposes:

- Providing pictures and video of the water target at the same time of the LiDAR measurement.
- Computing the water surface velocity thanks to the combination with the LiDAR measurement.

The water surface velocity is also computed at the same time of the LiDAR measurement and is provided as a matrix with one speed value and direction per pixel of the video. The matrix is the result of the average of a 5 second video.

Implementation: The Micro-Stations are very easy to install. With a compact form factor, a micro-station can be schematized by a box with a format of 20 x 120 cm, weighing 720 grams, and can be easily fixed to any stable structure close to a water body or on a bridge, using screws or a magnet if the structure (or the bridge) is metallic. The Micro-Station is self-sufficient in terms of power thanks to a solar panel and a battery (if the solar panel is out of order, the battery is designed to ensure 15 days of autonomy).

Calibration: The micro-station altimetric reference is computed from GNSS measurements performed by the station itself. A GNSS chip is embedded in the station. The distance between the LiDAR reference and the GNSS antenna is a standard because we use a generic boom arm to install the micro-stations. The measurements are provided with respect to an absolute reference, ellipsoid (WGS84) or local geoid (orthometric height).

Performances: The water surface height is provided with a centimetre level accuracy. The standard deviation of the 30 seconds of LiDAR measurement is provided with the median. Water surface height comparison has been performed between the vorteX.io micro-station and Vigicrues sensors at the same place and for 10 months. The results are shown in the following diagnoses for stations installed in Mazères (Ariège, South of France) on the Hers River.

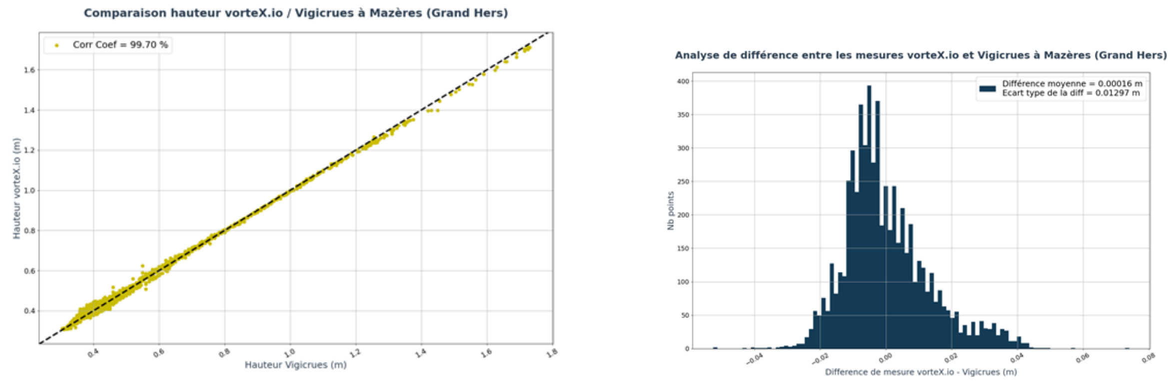


Figure 27: Scatter plot of the water surface height measured by a Vigicrues station and a vorteX.io micro-station at Mazères (left). Histogram of the height differences (right)

The water surface velocity is also provided with an accuracy of 0.1 m/s.

Strengths: The system is easy to install with a fast commissioning. The station provides different water measurements and pictures / videos of the water body in real time. The micro-station is completely autonomous in terms of power supply and connectivity. The micro-station can be programmed in order to perform measurements at the exact date and time of the satellite pass (thanks to the connectivity system and the vorteX.io automatic remote control, and the satellite ephemeris).

Drawbacks: The micro-station needs to be installed on a fixed structure. The micro-station must have a nadir point of view above the water surface.

5.3.1.2 Gauge with camera

Description: This sensor measures the water level by camera. It uses a fixed camera to obtain information on water levels.

Figure 28: Example of a sensor combining a camera and a limnimetric gauge

Measurement principle: The measurement approach is based on the automatic detection of the waterline in image sequences. The smart camera enables this contactless approach to measuring and monitoring levels of standing or moving waters. The water line is detected in the images thanks to the installation of a limnimetric scale on a fixed structure in the water (a bridge pier, a wall, etc ...). The camera is pointed to the limnimetric scale. The water level is read on the limnimetric scale thanks to a machine learning algorithm.

Implementation: A limnimetric gauge is fixed on a solid structure (a wall, a bridge pier, etc...) into the water body. A high-quality camera is installed so as to have a diagonal view of the water body and to have the limnimetric scale inside its field of view. The camera must be installed high up to optimise its field of view (on a metallic pole). Power supply and connectivity must be added.

Calibration: Calibration is made during the installation by precisely measuring the coordinates of at least 4 ground reference points (GRP) into the field of view of the camera using a high precision GNSS receiver and antenna. The GRPs are positioned using a RTK processing. Then, each image of the camera is orthorectified and georeferenced using the GRPs. An additional water level measurement can be performed using GNSS to validate the calibration process.

Performances: The water level accuracy depends on the camera resolution and the distance between the camera and the limnimetric scale. For example, a pixel represents 0.4 to 1 cm in the real world according to the level of zoom with a 5 MP camera located at 20m from the limnimetric scale. This same pixel corresponds to 1 – 2 cm for an installation 40m from the same 5MP camera

Strengths: As the camera is a contactless sensor, it is installed away from a waterway or reservoir. It is not submerged and therefore the system is protected from floating debris. The sensor has the advantage of operating from images. These images are useful for assessing a hydrological event briefly or communicating on a section's hydraulic reality.

Drawbacks: The installation is not easy as it requires a fixed structure to install a classical limnimetric gauge Moreover, a point of view compatible with the camera characteristics must be found to install the camera. The sensor is not affordable, and a high-speed connectivity is mandatory to send pictures. Power supply and connectivity must be brought to the camera.

5.3.1.3 Citizen science

Description: OECS / LOCSS share the same approach: involve citizens in the knowledge of our planet's freshwater resources evolution and contribute to the calibration of satellite data.

Lake Observations by Citizen Scientists & Satellites (LOCSS, https://www.locss.org/) is an effort to better understand how the volume of water in lakes is changing over time. Are lake volumes affected most by precipitation, water table height, evaporation or some other factors? Knowing the answer to this question will help better understand how water moves in relation to these lakes and the surrounding land and what that may mean for lake users and these ecosystems. The LOCSS project is working with a network of citizen scientists who are reporting lake height by reading simple lake gauges. These measurements are then combined with surface area measurements of the lake derived from satellite images. By knowing the changes in both lake height and lake surface area, researchers can understand how the volume of water in a given lake is changing over time.

Although satellites capable of measuring lake level are now well-established (e.g., Jason-2/3, Sentinel 3, and Sentinel 6 Michael Freilich), there has been no systematic evaluation of their capabilities over small lakes. Meanwhile, the SWOT mission, launched in 2022, will dramatically expand such measurements in lakes as small as 250 m x 250 m. The LOCSS project engages citizen scientists in collecting measurements for validating SWOT inundation extent datasets, data similar to those collected by the SWOT project validation team but much more geographically extensive.

While LOCSS data can be used to understand lake processes on their own, they also represent a potentially vital source of validation data for satellite altimeters (e.g., Jason 2/3, Jason-CS Sentinel 6 Michael Freilich, Sentinel 3A&B). Altimetry measurements of lake water levels have been extensively validated over lakes larger than approximately 100 km2 (e.g. Charon M. Birkett, 1998 [RD43]; C. M. Birkett & Beckley, 2010 [RD44]; Crétaux et al., 2016 [RD45], 2018 [RD11]; Crétaux & Birkett 2006 [RD46]; Ricko et al., 2012 [RD47]; Sulistioadi et al., 2015 [RD48] and many others), with only a handful of studies comparing against a very limited number of smaller lakes (Arsen et al., 2015 [RD49]; Baup et al., 2014 [RD50]; Nielsen et al., 2020 [RD9]). Because LOCSS data are highly accurate (a precision of the order of 1 cm has been demonstrated) and mostly collected in relatively small lakes, we can use them directly to validate altimetry data and, perhaps more importantly, to better understand the conditions under which altimeters are and are not accurate. This work will be even more important with the anticipated launch of the SWOT mission.

Table 6: Current LOCSS lakes that fall under nadir altimetry tracks

Lakes	Satellite	Area (km²)	Region	Observations
Phelps Lake	S3A	64.5	NC	341
Lake Mattamuskeet West	S3B	57.6	NC	158
Bay Tree Lake	S3B	5.8	NC	442
Catfish Lake	S3A	3.8	NC	42
Lake Sammamish	S3A	18.6	WA	205
Pattison Lake*	S3B	1	WA	0
McIntosh Lake*	S3B	0.5	WA	0
Phantom Lake (WA)	S3B	0.3	WA	247
Kentuck Lake	S3A	4	WI	1
Long Lake (WI)	S3B	1.1	WI	58
Paya Lake	S3B	0.4	WI	65
Phantom Lake (WI)	S3A	0.2	WI	86

LOCSS focus considerable effort during the pilot phase on expanding the LOCSS lake network and on the limited subset of lakes that fall beneath a Sentinel 3 or Jason 2/3/Sentinel 6 nadir altimetry track. In the current LOCSS network, twelve altimeter-observed lakes that are either currently observed or in which gauge installation is in progress (

Table 6 above). While these lakes will provide highly useful information, there is a clear need to add many additional lakes to the LOCSS network in order to effectively validate nadir altimeters over small lakes. A suite of potential validation lakes in regions where LOCSS have existing partners and gauge networks has been identified. The number of lakes per region that underlie Sentinel 3A, Sentinel 3B, or Jason 2/3/Sentinel 6 ground tracks is listed in Table 7. From these suitable lakes, LOCSS plan to install approximately 50 additional rules.

Table 7: Current and planned gauges in the LOCSS network

Region	Current/Planned LOCSS & Partner Lakes	Nadir Altimetry Candidate Lakes	Planned for Pilot Phase	Planned for Continuation Phase
Washington, USA	33	110	5-10	5-10
New England, USA	3	356	10-20	10-20
Illinois, USA	17	19	5-10	1-5
Wisconsin, USA*	32	349	0	10
North Carolina, USA	12	1	0-1	0
Additional USA Regions	0	>1000	0	100
Bangladesh*	4	15	10	20
Nepal	0	0	1	4
India	4	0	0	0
Pakistan	4	13	5	10
France*	12	>1000	25-30	25-30
Canada*	0	>1000	5-10	100
Total	**121**		**66-97**	**265-309**
*Partner Project			**Total**	**452-527**

Measurement principle: Human reading of the water level on a plain rule installed on site. The water levels of the corresponding lake have also been measured by a GPS mean during a dedicated campaign, we have thus an absolute information water level information toward the ellipsoid.

Figure 29: Picture of the LOCSS team installing a gauge

Implementation: A plain rule is installed on a structure, could be a peer, a ponton, a bridge pile, etc …

Calibration: There is no absolute calibration performed - we assume that the rule installation remains a fixed point (no GPS levelling is performed on the structure).

Performances: Comparison of measurements by citizen scientists and pressure transducers demonstrate that citizen scientists produce highly accurate measurements, with a mean absolute error of 1.6 cm, approximately twice the estimated uncertainty in the pressure transducer measurements (0.8 cm) (Figure 30B).

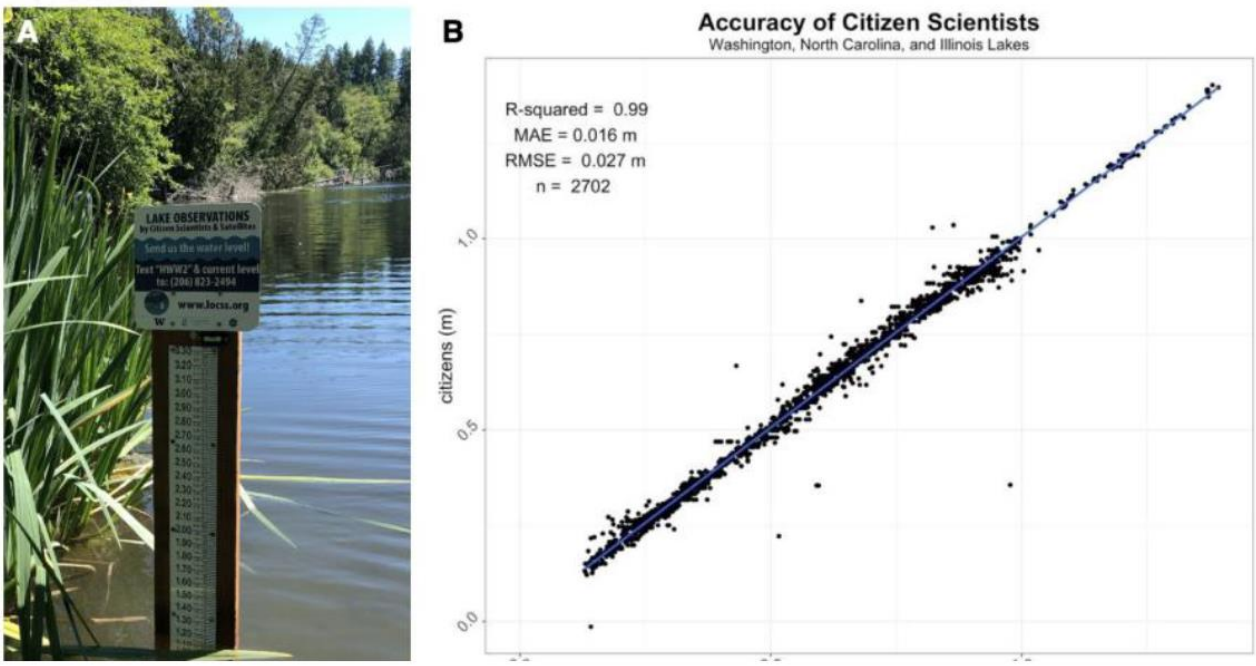


Figure 30: (A) example of a LOCSS gauge; (B) Scatterplot showing validation of LOCSS water level data compared against automated pressure sensors

Strengths: Very cheap (rule cost is of the order of 50€), allows to implement a citizen science approach.

A useful means to complement automatic sensor means, for example the rule can be installed close to an automatic station: the citizen science measurement is of interest to calibrate the automatic sensor stability.

Drawbacks: Relying on citizen science, so there is there is no commitment in collecting lots of data, nor to collect data at the time of the satellite overpass. The amount of data collected may be season dependent.

5.3.2 Moving sensors

5.3.2.1 Towed GNSS carpet

Description: CalNaGeo is a towed dedicated device. It could be towed on sea, on river or lake whatever water state (calm river or strong current, sea state up to 6). It is 11 metres long, 2 metres wide, and weighs 100 kg. The GNSS antenna is mounted on a deformable carpet which follows the shape of the water without extra movement (if the antenna was fixed on a boat for example). GNSS Receiver, batteries and WIFI transmitter are in the inflatable boat. An available option is an ADCP to measure flow, current and depth.

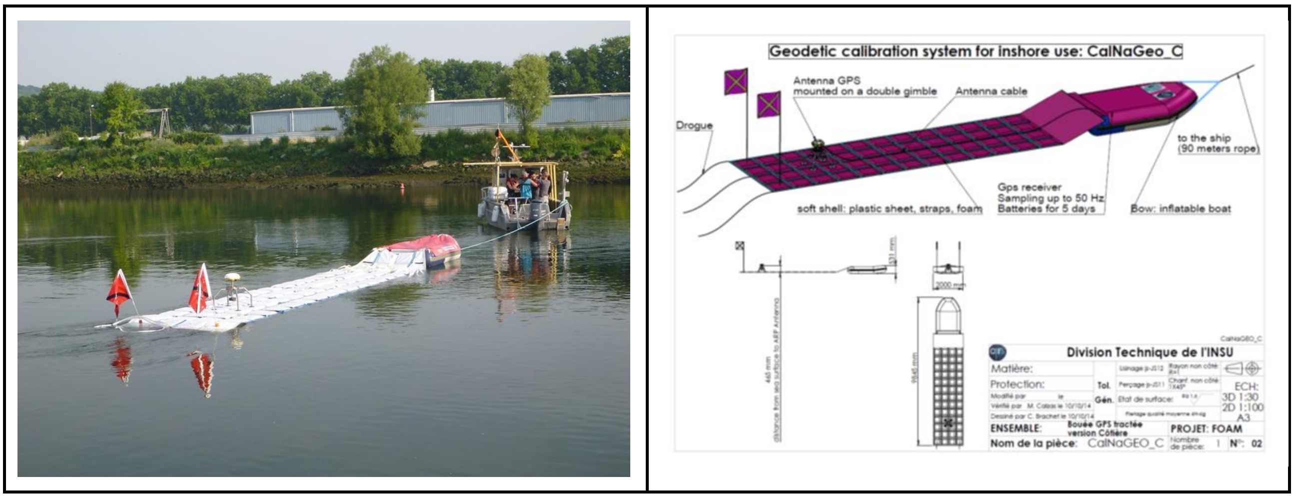


Figure 31: Picture of CalNaGeo (left); Scheme of CalNaGeo (right)

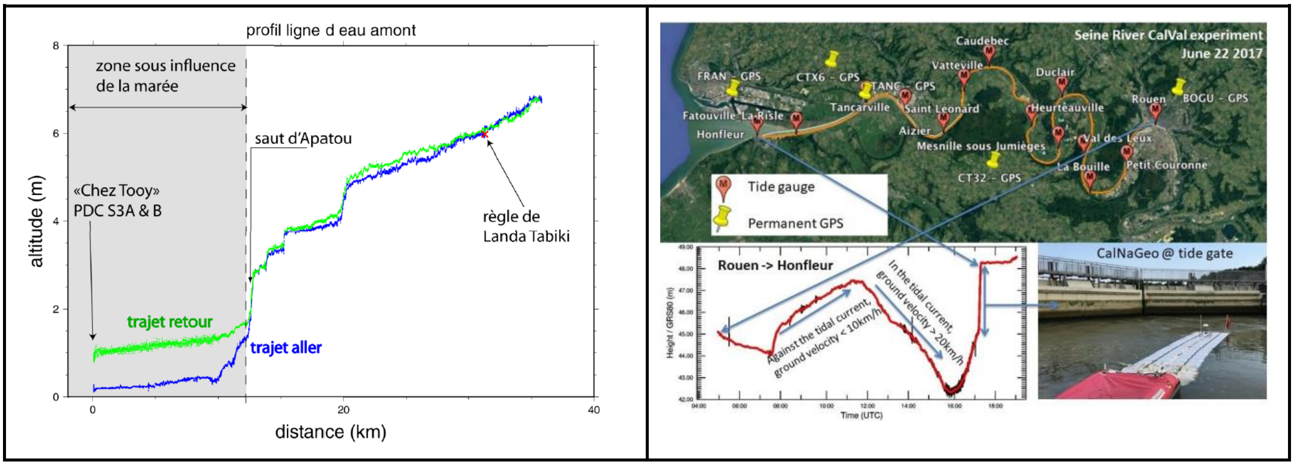


Figure 32: Example of measurements: Maroni River (left); Seine river (right)

Measurement principle: This Device is dedicated to measuring water height over long distances, towed by a boat. This system consists of a GNSS antenna mounted on a deformable floating sheet towed by a boat, ensuring good coupling with the sea surface and ideally, a constant antenna height above the water. The antenna height is precisely measured before the campaign.

Implementation: The GNSS carpet is towed by a boat (don't need a big boat with a big engine). An easy access to the water is mandatory to launch the boat and the GNSS carpet.

Calibration: Before the campaign, the antenna height above water needs to be carefully measured. Then this height remains constant at every use. Such a measurement can be made at a few millimetres level.

Performances: The accuracy is about 1 cm. The GNSS carpet has 1 week of lifetime with a single battery pack (could be improved if we add batteries).

Strengths: The GNSS carpet can provide measurements whatever water state, even at high speed (up to 10 knots). It is one of the very few means to actually measure water surface slope.

Drawbacks: Must be towed by a boat, relatively heavy and slow. An easy access to the water is mandatory to launch the boat and the GNSS carpet. The water body must be navigable.

5.3.2.2 Boat embedded GNSS and acoustic

Description: Cyclopée is a device based on a GNSS receiver coupled with an altimeter. This system is designed to be used on a boat, at up to 20 knots speed (maybe more, TBC). To compensate for the vertical ship movement, it measures (up to 30 Hz) the distance between the reference of the GNSS antenna down to the water with an acoustic sensor. The whole system is mounted on a stabilised arm to maintain the GNSS antenna horizontal and consequently the distance to the water vertical.

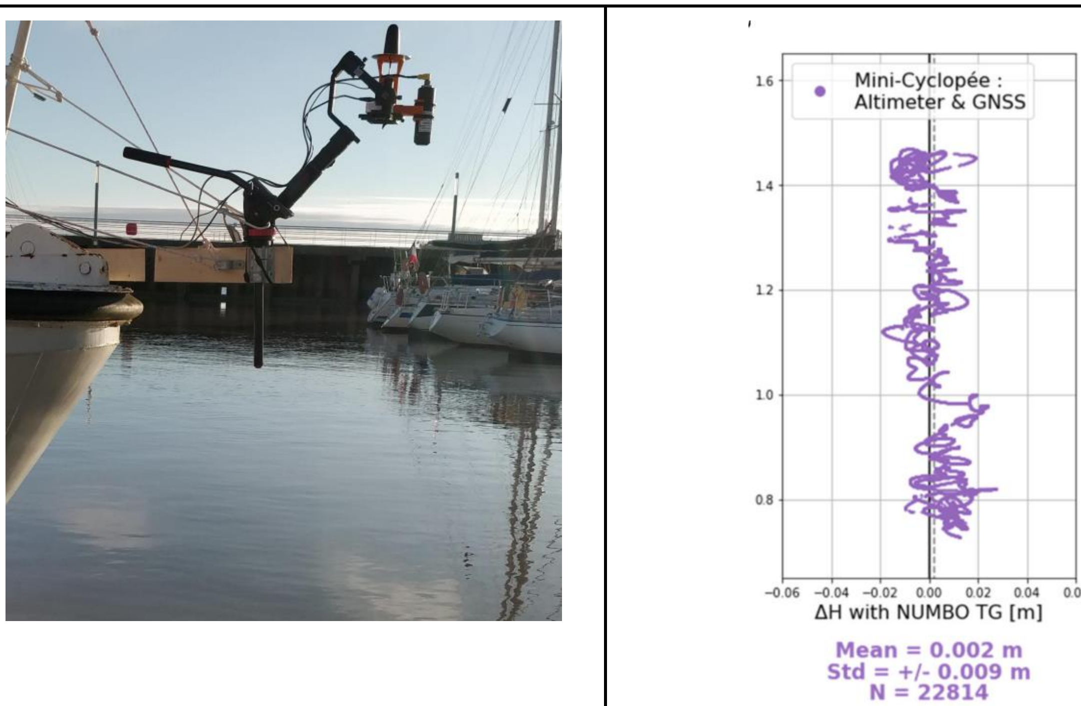


Figure 33: Picture of Cyclopée mounted on the bow of a ship (right); Differences between Cyclopée water height measurement and a tide gauge (right)

Measurement principle: The principle consists in a GNSS measurement combined with an acoustic altimeter to measure the distance between the antenna and the water.

Implementation: The system can be installed on a boat or a surface Drone.

Calibration: The distance measured by the acoustic altimeter needs to be calibrated before the campaign and can be realised in a laboratory. A GNSS receiver can be used to measure the water surface height and calibrate the measurement system.

Performances: Cyclopée has already demonstrated an accuracy of about 1 cm.

Strengths: Easy to install on any boat, small and affordable.

Drawbacks: The device is not completely watertight. As the system is installed on a boat, easy access to the water is mandatory to launch the boat. The water body must be navigable.

5.3.2.3 Unmanned surface vessels

Description: Unmanned Surface Vessels are boats or ships that operate on the surface of the water without a crew. In the frame of Cal/Val activities, this system is used as a platform and is equipped with a GNSS receiver and antenna. The distance between the antenna and the water surface is measured precisely manually (WaSP system, Pitcher et al. 2020 [RD51]) or using an acoustic sensor (mini Cyclopée system). Two systems have already been used for Cal/Val activities, the WaSP system developed by US teams, and mini Cyclopée mounted on a PAMELI drone developed by French teams.

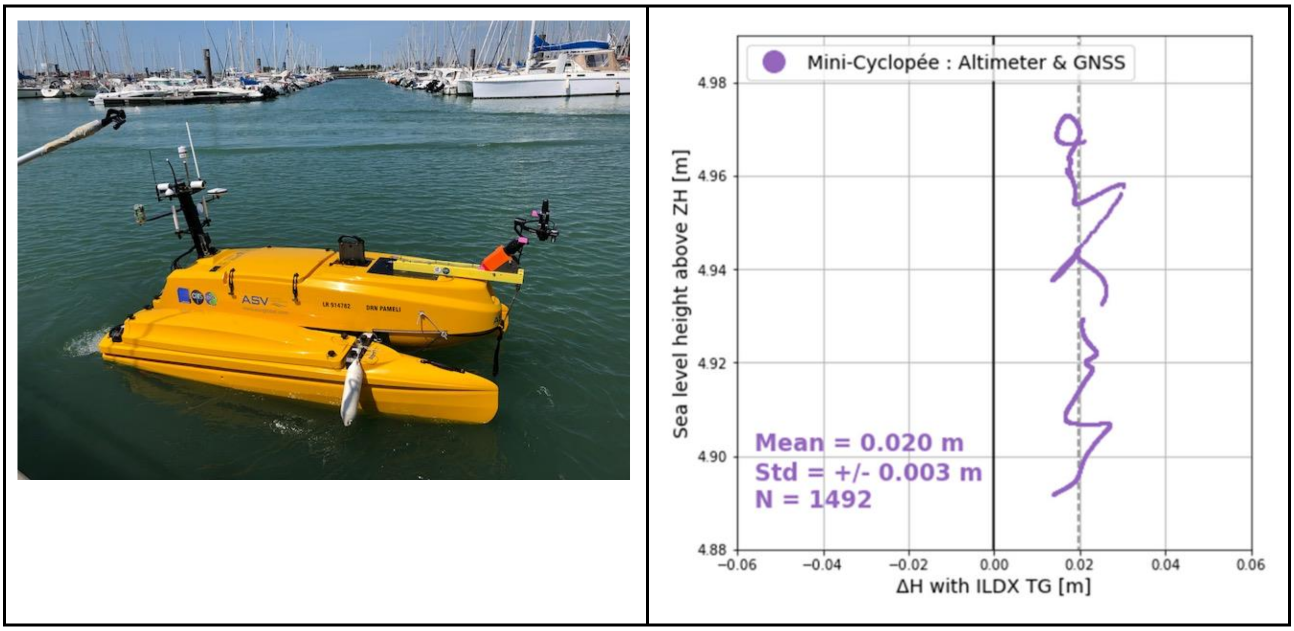


Figure 34: Picture of Mini-Cyclopée mounted on a PAMELI drone (right); Differences between Mini-Cyclopée water height measurement and a tide gauge (right)

Figure 35: Picture of the WaSP system

<u>Measurement principle:</u> For the mini Cyclopée embedded on the PAMELI drone system, the principle is like the Cyclopée system. It must be noted that other measurement systems can be added to this unmanned vessel (ADCP, echo sounder…).

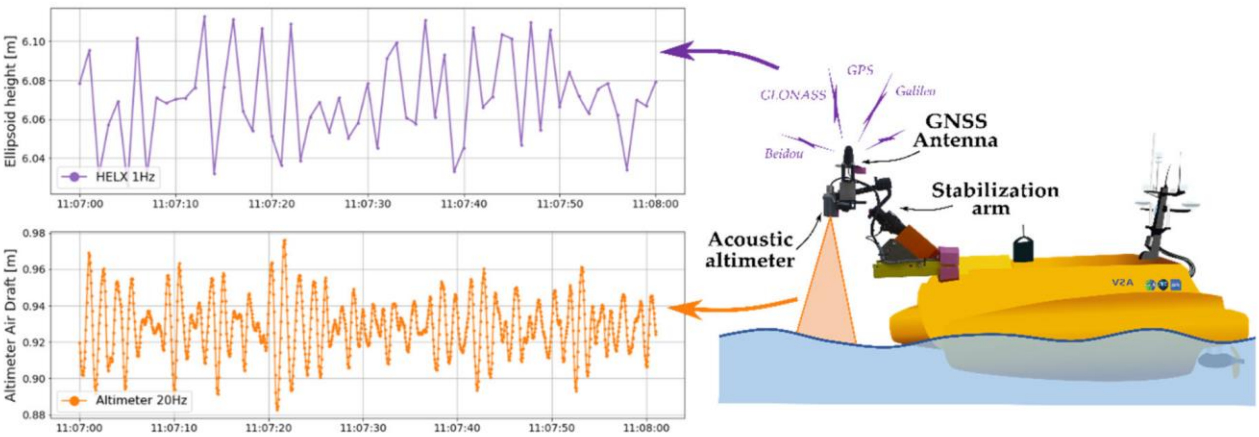


Figure 43: Measurement principle of Mini-Cyclopée embedded on a PAMELI drone

For the WaSP system, the measurement system is like the GNSS sensor embedded on boats.

Implementation: The system is installed on a drone ship and can be used on rivers, lakes and estuaries.

Calibration: Same as all GNSS receivers: close to a reference point (tide gauge, base GNSS reference station) or PPP calculation.

Performances: The WaSP system has demonstrated its ability to reach an accuracy of 3 to 5 cm (Pitcher et al. 2020 [RD51]). The Mini Cyclopée embedded on the PAMELI system can provide water surface height at a centimetre-level accuracy.

Strengths: The system is easy to deploy, small and affordable.

Drawbacks: Easy access to the water is mandatory to launch the drone system. The water body must be navigable for a drone. The water state should not be too rough, and the water flow not too strong.

5.3.2.4 Light-weighted altimeter embedded under a drone

Description: For one-shot or periodic field campaigns, vorteX.io proposes an innovative and interesting solution: a light-weight altimeter embedded on flying drones. Thanks to the flexibility and ease of deployment of the drone, the system can acquire data over long distances, whatever the terrain conditions and the accessibility of the water body. Orthophotos of the overflown zone can be generated thanks to the on-board camera, which can be very useful for assessing water roughness, water extent, surrounding terrain, etc. This information proves to be very valuable to derive higher level products.

Figure 36: Picture of a flying drone with the vorteX.io light-weight altimeter

Measurement principle: The light-weight altimeter uses a combination of a LiDAR and a camera, and embarks a precise GNSS sensor and an inertial measurement unit (IMU) in order to correct for drone movement to provide water surface height with centimetre-level accuracy all along the drone flight. The drone deployment uses a GNSS base as reference, as illustrated in the following figure.

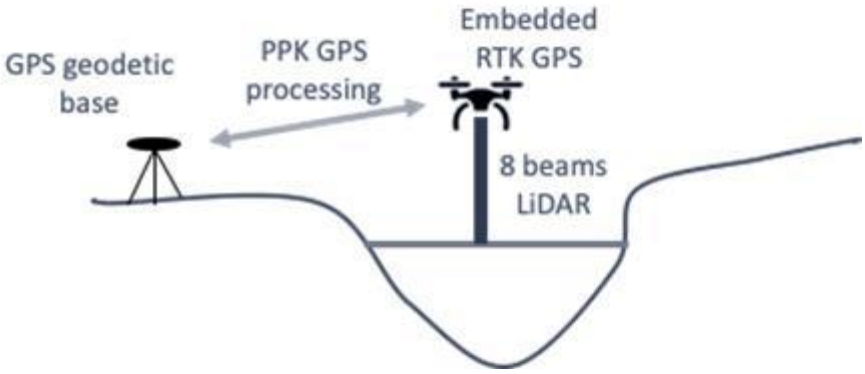


Figure 37: Measurement principle of the vorteX.io light-weight altimeter

This GNSS base is required to perform the Kinematic Post-processing needed to precisely position the lightweight altimeter and then to provide centimetre-level water surface height.

The elevation measurements are provided by a specific wide swath LiDAR: 8 beams spread over a 16.3° swath in order to guarantee the correct measurement of the surface during the drone flight. A specific post-processing is performed to eliminate outliers and unwanted data (land data, vegetation, etc.).

Orthophotos are built from the images acquired by the camera and a water mask is derived. An editing is performed to remove all elevation data over land using this mask. Editing is also performed related to the flight quality: Even if the UAV is programmed to follow a predefined flight plan with a specific constant altitude and velocity in order to provide the best possible measurements, it may happen for a few seconds and due to weather conditions (gust of wind) that the altitude and velocity values deviate too much from the requirements. In this case, an automatic editing removes those points from the time series. This post-processing guarantees the reliability of the measurements. Moreover, the light-weight altimeter has its own Wi-Fi network and a specific dashboard that allows the drone operator to check the measurement quality during the drone flight.

Implementation: Thanks to the flexibility and ease of deployment of the drone, the system can acquire data over long distances, whatever the terrain conditions and the accessibility of the water body, if only weather conditions are good enough to fly (wind limit of ~50 km/h). The drone can also be deployed from a boat, allowing it to map large lakes or long distances along rivers and estuaries.

A drone deployment is divided into the following steps:

Before drone deployment

1. Determine the flight plan
2. Prepare flight authorisations if needed (not always the case)

During the deployment

3. Install the GNSS base with a full sky point of view
4. Calibrate the IMU of the lightweight altimeter
5. Fix the instrument to the drone
6. Perform the drone flights

After deployment

7. Process GNSS measurements of the GNSS base using a PPP (Precise Point Positioning) processing
8. Process the GNSS measurements of the lightweight altimeter using a PPK (Post Processing Kinematic) processing
9. Compute elevation measurement by combining the LiDAR measurements and the GNSS measurements
10. Correct from any mispointing
11. Perform a specific editing and selection on the WSH measurements
12. Store data into a NetCDF format for users

Calibration: Thanks to the use of three constellations (GALILEO, GPS, GLONASS) and a two-frequency GNSS system, the positioning is valid for base length up to 70 km. Drone measurements are calibrated during each campaign by flying over in-situ stations or the GNSS base to perform a reference measurement.

Performances: Drone campaigns have been successfully conducted many times in 2020 in collaboration with CNES, over long distances and different categories of water bodies (32 km on the Saône river, 60 km on the Rhine River and surrounding lakes, 58 km over the Geneva Lake, etc.). During these campaigns, Vigicrues stations have been overflown by the drone and the measurements from the vorteX.io lightweight altimeter has been compared to the measurements of the Vigicrues stations. Results are shown in the following figure.

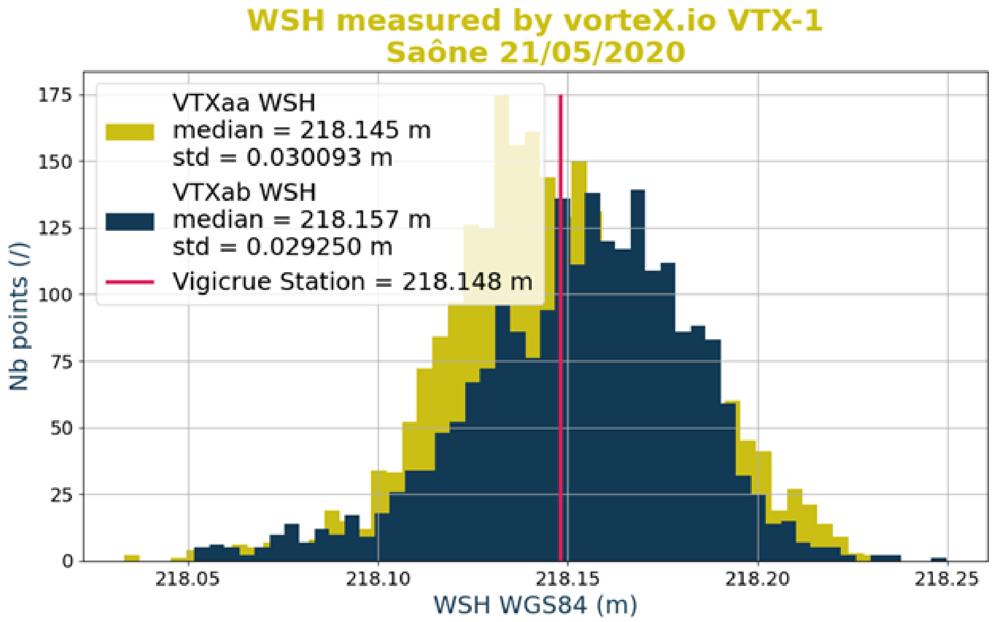


Figure 38: Comparison of 2 vorteX.io light-weight altimeter embedded on 2 drones with a Vigicrues station over the Saône river

As two drones have overflown the Vigicrues station located at Tournus on the Saône river, two instruments have been used. The measured accuracy is below the centimetre for both lightweight altimeters while the standard deviation is about 3 cm for both instruments during a 20 minutes flight.

Strengths: The vorteX.io lightweight altimeter allows measuring water surface height with a centimetre level accuracy all along drone flights. Drones are easy to deploy and allow measurements exactly below the satellite pass. Drones also allow WSH measurements over long distances even on non-navigable water bodies or on water bodies with a very complex access. The deployment costs are affordable.

Drawbacks: Drones need favourable weather conditions to be deployed. The main constraint is the wind speed with a maximum of 50 km/h.

Drone regulations can be restrictive depending on the country and the deployment zone (airport proximity, Industrial site, etc ...)

5.3.2.5 Airborne LiDAR

Description: The airborne LiDAR is a “compact” laser-based system designed for the acquisition of topographic and return signal intensity data from a variety of airborne platforms. The data is computed using range and return signal intensity measurements recorded in flight along with position and attitude data derived from airborne GNSS and inertial subsystems. The LiDAR system weights around 100 kg and is composed by:

- The scanner assembly.
- The system electronics.
- Interconnecting cables.
- An operator interface.

- A vibration isolated interface plate assembly for both scanner and electronics.
- GNSS receiver and antenna.

Measurement principle: By measuring the location (latitude, longitude and altitude) and attitude (roll, pitch and heading) of the aircraft, the distance to ground and scan angle (with respect to the base of the scanner housing), a ground position for the impact point of each laser pulse can be determined.

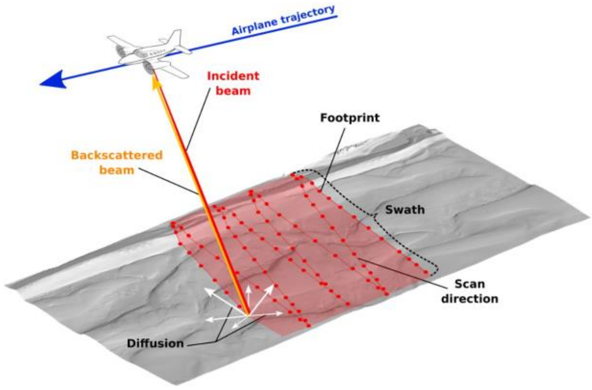


Figure 39: Measurement principle of the airborne LiDAR system

Implementation: The installation is done in a specific plane. Then the plane flight is driven by weather conditions, authorisations and the air traffic control.

Calibration: Calibration is done by using GNSS measurements of overflown ground control points / ground reference points (GCP or GRP).

Performances: A standard flight leads to a point density of about 4 points / m^2 on average, but of course, it depends on the plane speed and altitude. The accuracy of the retrieved water surface height has been evaluated to ~10 cm during the Gironde campaign performed in 2018.

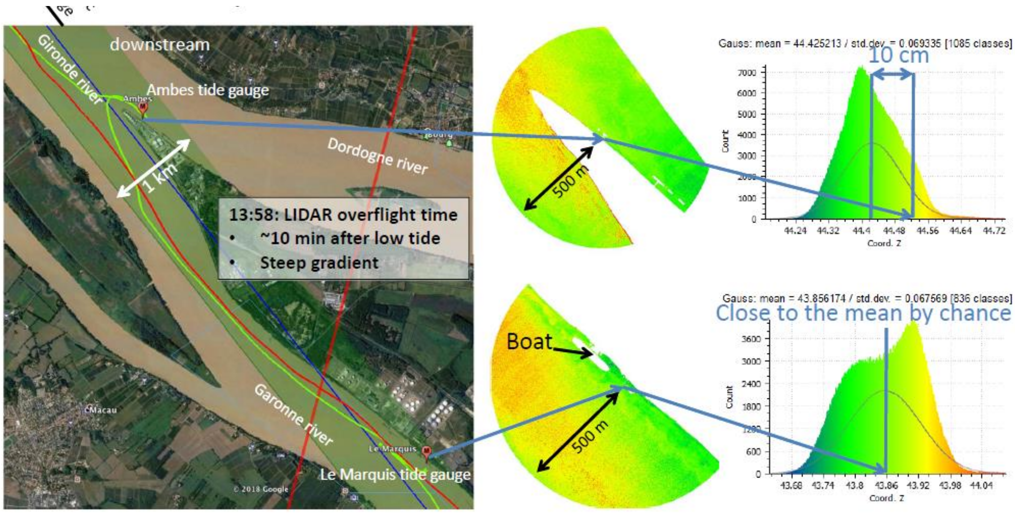


Figure 40: Example of airborne LiDAR measurements acquired during the Gironde campaign

Strengths: Very high point density which allows to perform averages. Very large zones can be measured thanks to the aircraft.

Drawbacks: With constraints on weather conditions, regulations and air traffic, it is not easy to deploy the aircraft when it is needed. The system is not flexible. The system is expensive.

5.4 Existing networks

5.4.1 Role of the European Environment Agency (EEA)

The EEA (https://www.eea.europa.eu/en) is an European agency tasked with providing sound, independent information on the environment. It operates as a major information source for those involved in developing, adopting, implementing and evaluating environmental policy, and also the general public.

The European Environment Information and Observation Network (Eionet) is a partnership network of the European Environment Agency (EEA) and its 38 members and cooperating countries. EEA and Eionet gather and develop data, knowledge, and advice to policy makers about Europe's environment.

Overall, Eionet consists of the EEA and circa 400 national institutions from 38 countries, with expertise in environmental issues, and eight centers of thematic expertise contracted by the EEA, called European Topic Centers (ETCs).

The EEA is responsible for developing Eionet and coordinating its activities together with National Focal Points (NFPs) in the countries. The NFPs are the country institutions appointed to serve as the primary link between the EEA and the country. NFPs facilitate and coordinate networks of national experts involved in national activities related to the EEA work program.

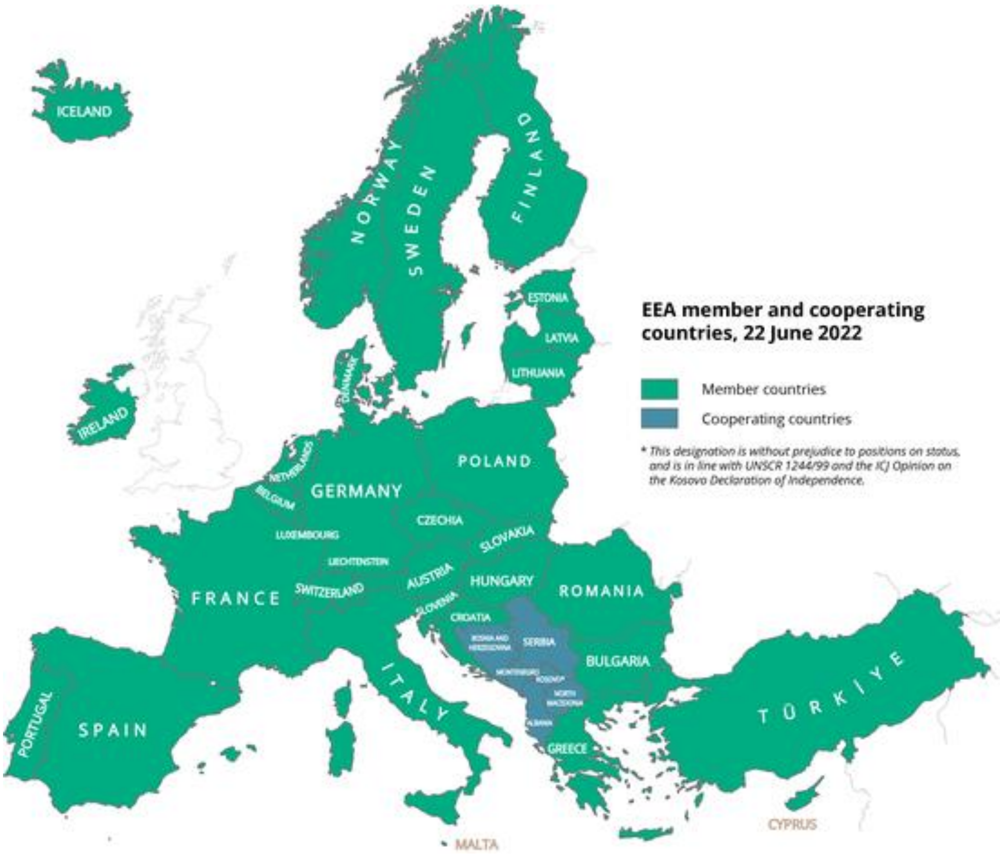


Figure 41: EEA member and cooperating countries (status on 22 June 2022)

A meeting was held with the EEA as part of the St3TART project to discuss data from existing networks in Europe. As a result, the EEA cannot disseminate the data collected but can facilitate access to national public network data from the 38 members for the purposes of the project.

5.4.2 French National network

The French national network has been deployed for many years now and is composed of 3500 measuring stations (of which 2400 currently in service) located on the French rivers. The “banque hydro” is the national data bank for hydrometry and hydrology, it stores the water level measurements. Data can be accessed using the following website: http://hydro.eaufrance.fr/indexd.php. The “banque hydro” accommodate together data from the regional organisations (DREAL) responsible for the operation of the network, both from Metropolitan France and from overseas (e.g. French Guiana).

This database has a depth of data of more than 30 years, and allows access to:

- Information on the station such as its geographical location, the quality and availability of measurements, its history.
- Daily flow data in the form of tables or graphs (flow data are not available on all the network, only a part of the network is providing water flow measurements).
- Statistics on the flows calculated over the availability period.
- Comparisons of flow data in relation to median flows, or to low or high values with return periods of the order of 5 years.
- Other functionalities allowing to compare two series of data.

In the framework of the St3TART project, we show on the following figure all Vigicrues stations at less than 1 km from a Sentinel-3 track (Sentinel-3A in blue, Sentinel-3B in green). It represents 114 stations located within 1 km of a Sentinel-3A track, and also 114 stations located within 1 km of a Sentinel-3B track.

But in these numbers, not all the stations are necessarily usable. In fact, some stations are only used for flood management and thus only provide a relative height, without any GNSS reference level. For these stations, a GNSS measurement of the 0 of the gauges must be performed to make them usable for the St3TART project.

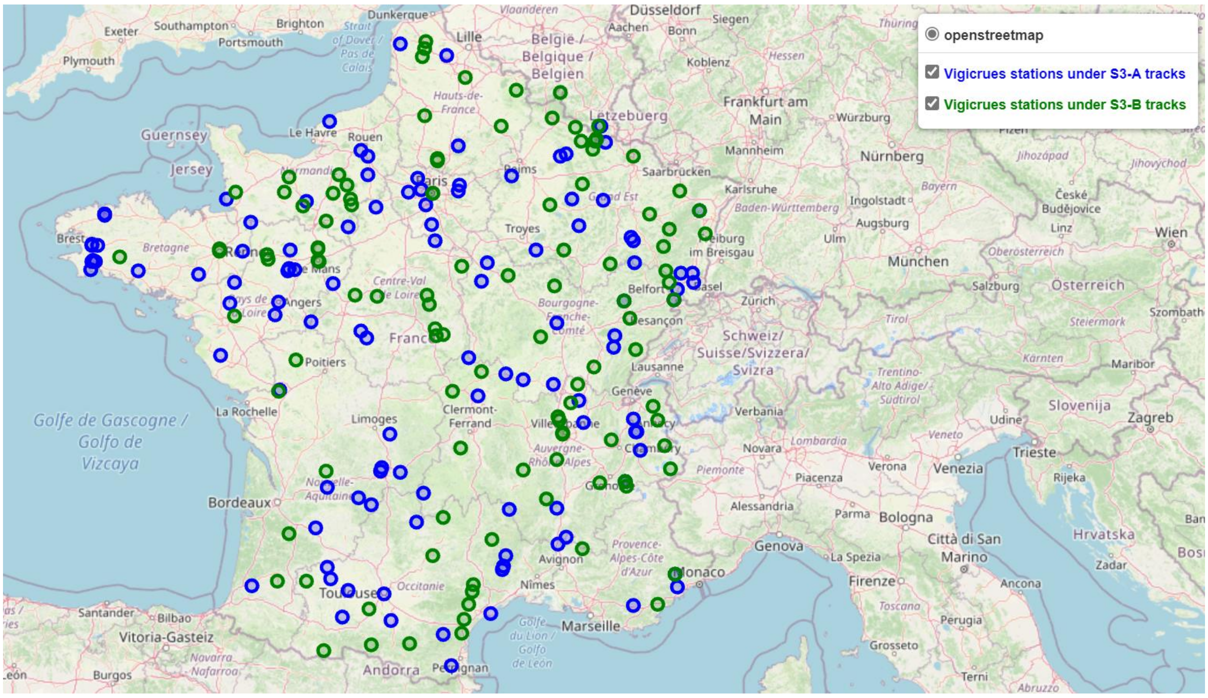


Figure 42: Map of Vigicrues stations from the French national network located at less than 1km from a Sentinel-3A track (in blue) or from a Sentinel-3B track (in green) in metropolitan France

There are additional valuable networks belonging to river management organisations in charge of hydro power plants (such as EDF managing the 12 power plants along the Rhine, but also some reservoirs dedicated to the cooling nuclear plant) or navigation (like CNR over the Rhone River). Therefore, these networks are most of the time confidential and difficult to obtain. A strong effort is put on the establishment of procedures to access these valuable data.

Another important actor in France is VNF, Voies Navigables de France, in charge of the management of canals connecting regions together. Rhine to Rhone, Bourgogne to Champagne for example. VNF collects water level and water volume for lakes, acting as water resources to infill canals, but also along canals.

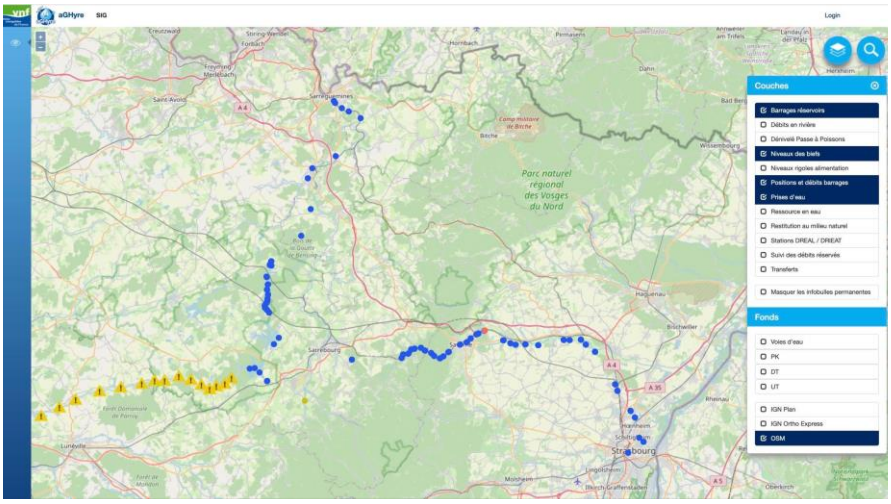


Figure 43: Snapshot of the prototype of the aGHyre database set up by VNF providing water levels on canals and reservoirs

For lakes and reservoirs, the picture is much more diverse, in complement of the already cited EDF and VNF, there are many actors involved in water bodies management and by the way collecting water levels. These correspond to at local level Municipality technical services, such as Strasbourg Eurométrople, Mulhouse municipality but also at a regional level, Services such as the Collectivité Européenne d Alsace (merging the Conseil Généraux du Haut and Bas Rhin). Access to all these water levels over lakes is not obvious and requires a lot of discussion and exchange with data owners.

It should also be noted that the equipment of the same measurement network can vary greatly between two stations that are nevertheless close. For example, while the water level values are retrieved automatically with a frequency of 5 minutes for the Stock Lake, it is done manually and on a daily basis for the Gondrexange pond, where an agent has to go and read the values on the scales.

One additional point to notice, particularly in a transboundary context such as along the Rhine, is the diversity of referential and coordinate systems. For example, the Schapi data are expressed in NTF_Paris_Lambert_Zone_II/IGN69, whereas on the other side of the Rhine, it is in DHDN_3_Degree_Gauss_Zone_3/ DHHN12 or DHHN92, and some others only referring to a local Zero…

5.4.3 German network

The organisational structure of the German in situ network is different from that of France. All inland waterways, including the Rhine, are owned and controlled by the national government through the Federal Waterways and Shipping Administration (WSV). As a scientific institution, the Federal Institute of Hydrology (BfG) is responsible for these waterways. Basically, BfG is the advisor body to both WSV and the Federal Ministry of Transport and Digital Infrastructure (BMVI) in all matters of utilization and management. Hydrological and hydraulic data at this federal level are disseminated through www.pegelonline.wsv.de.

In terms of data access, hydrological measurement and prediction archives are disseminated via the www.hochwasserzentralen.de (cf Figure 44). The portal directs any request, however, to the authorities at the state level. Figure 52 shows the distribution of water level stations over the upper, middle, and lower Rhine which are respectively maintained by the State Institute for the Environment, Measurements and Nature Conservation (LUBW) in Baden-Württemberg, the State Office for Environment in Rhineland-Palatinate and the State Agency for Nature, Environment and Consumer Protection (LUAUV) in North Rhine-Westphalia.

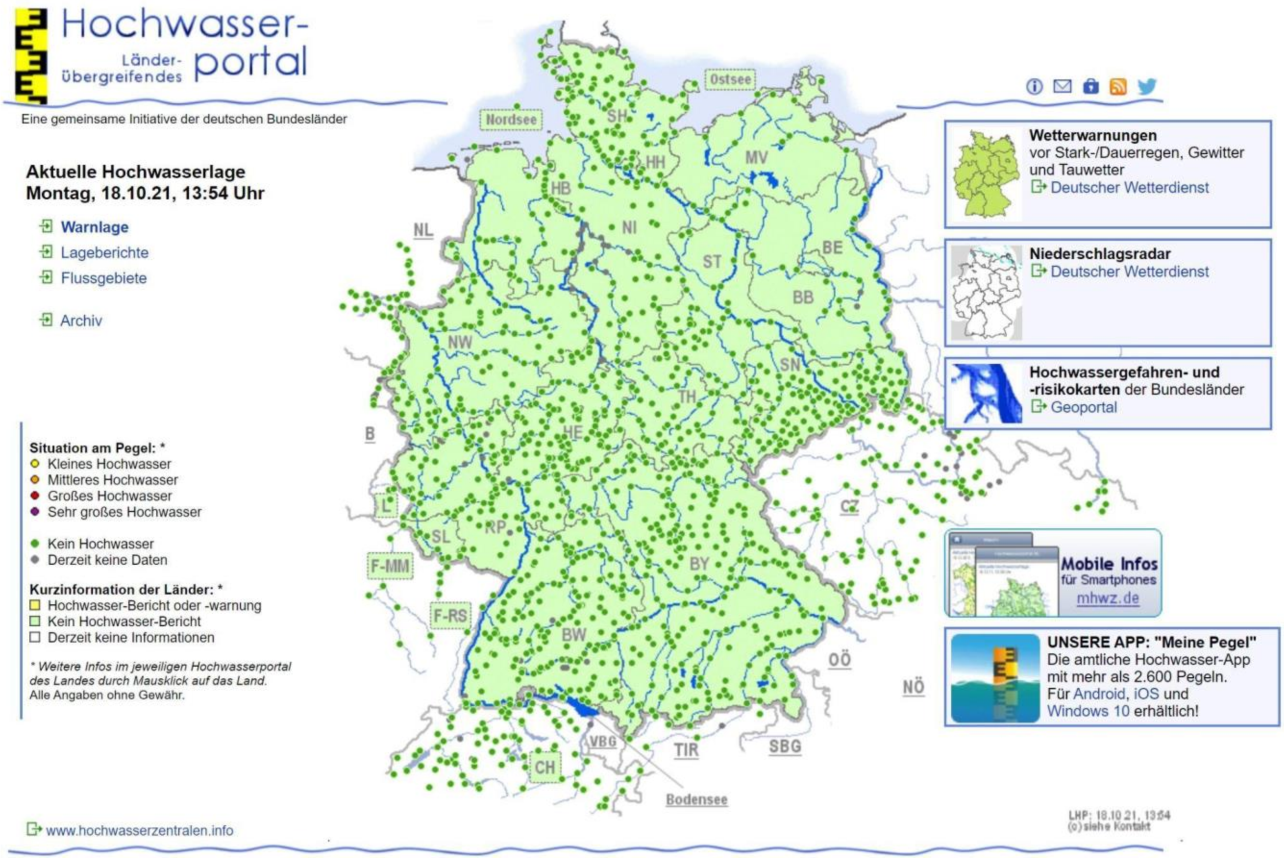


Figure 44: A snapshot of the website www.hochwasserzentralen.de

While the near-real-time data of stage and discharge as well as the predictions are publicly available, access to historical dataset is only possible by making official requests to the authorities. A pictorial overview of the level (or other measurement quantities) variation throughout the last two weeks is however available publicly. The actual measurement sampling interval at each station can go down to 15 minutes. The information is, however, made available at variable resolutions, depending on the station, the conditions (e.g., flood events), and the agreed rate for specific requests. The measurements are tied to the European Terrestrial Reference System 1989 (ETRS89). The height reference system of all height information is DHHN2016, height status (HST) 170, EPSG 7837.

Figure 45: Distribution of in situ stations over the Rhine in Germany. The snapshots are from http://www.hochwasser-rlp.de/

Within the framework of the St3TART project, SERTIT and GIS have access to the data through German authorities. SERTIT makes official requests to WSV, where it will further be passed down to BfG, regional, and probably even local authorities. The preliminary analysis over the 10 priority stations for Cal/Val shows that there are about 14 relevant in situ stations (multiple stations exist over the Lake Constance) from the German network. It is important to notice that there is no in situ station exactly at the location of altimetry crossings. This means that the in-situ data should be transferred to the VS location by correcting for the differences in their dynamic behaviour. To this end GIS currently negotiates with WSV (partial) access to a non-public database of WSV that contain along-river heights and slopes from shipborne measurements, potentially at 100-m-sampling.

Moreover, GIS has access to in situ river discharge provided by GRDC (https://www.bafg.de/GRDC). River discharge data are typically available close to the outlet of sub-basins, offering a rich network of available gauging stations (Figure 46).

Figure 46: Number of available in situ discharge data in GRDC database over the Rhine river basin (snapshot is taken from GIS internal part of HydroSat http://hydrosat.gis.uni-stuttgart.de)

5.4.4 Swiss network

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 comprises some 260 measuring stations. In addition to the water level in the lakes, the network also measures the flow rate of rivers at 200 locations.

In the frame of the St3TART project, we show in the following figure all Swiss stations at less than 1 km from a Sentinel-3 track (Sentinel-3A in blue, Sentinel-3B in green). It represents a number of 23 stations located within 1 km of a Sentinel-3A track, and also 11 stations located within 1 km of a Sentinel-3B track.

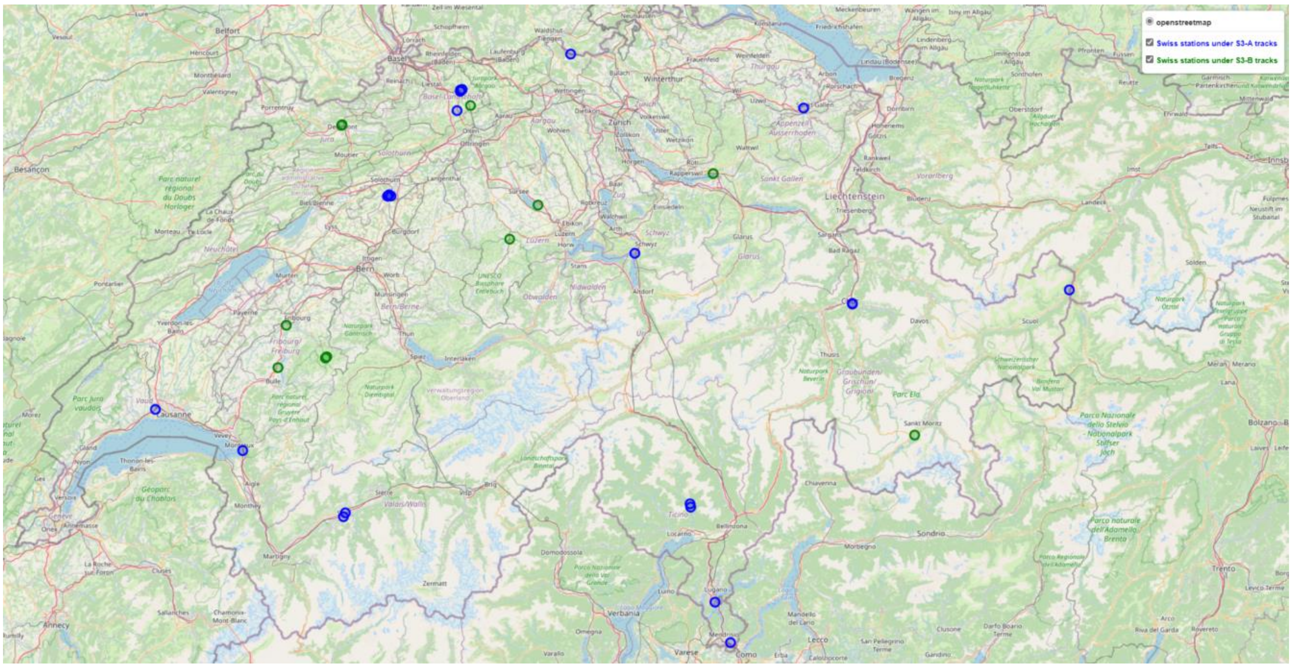


Figure 47: Map of FOEN stations from the Swiss network located at less than 1km from a Sentinel-3A track (in blue) or from a Sentinel-3B track (in green)

5.4.5 Italian network

The Italian hydro monitoring network is managed at regional level by different agencies. Based on a recent census carried out by ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale, https://www.isprambiente.gov.it/pre_meteo/idro/documenti_tavolo/Presentazioni_Rally/ISPRA_Il_monitoraggio_idrometrico_IT.pdf) Italian network includes a total of 1276 stations measuring water height and only 747 discharge.

For the Po basin, the Agenzia Interregionale del Fiume Po (AIPo) is in charge for the coordination of the hydraulic activity, management and improvement of the infrastructures for river navigation, environmental and river protection and coordination of the Flood Service. Managing the extreme events, AIPo participates to the forecasting and the monitoring. Specifically, the website of the agency (https://www.agenziapo.it/content/monitoraggio-idrografico-0) shows real-time and historical measurements that can be freely downloaded by any users (see Figure 48).

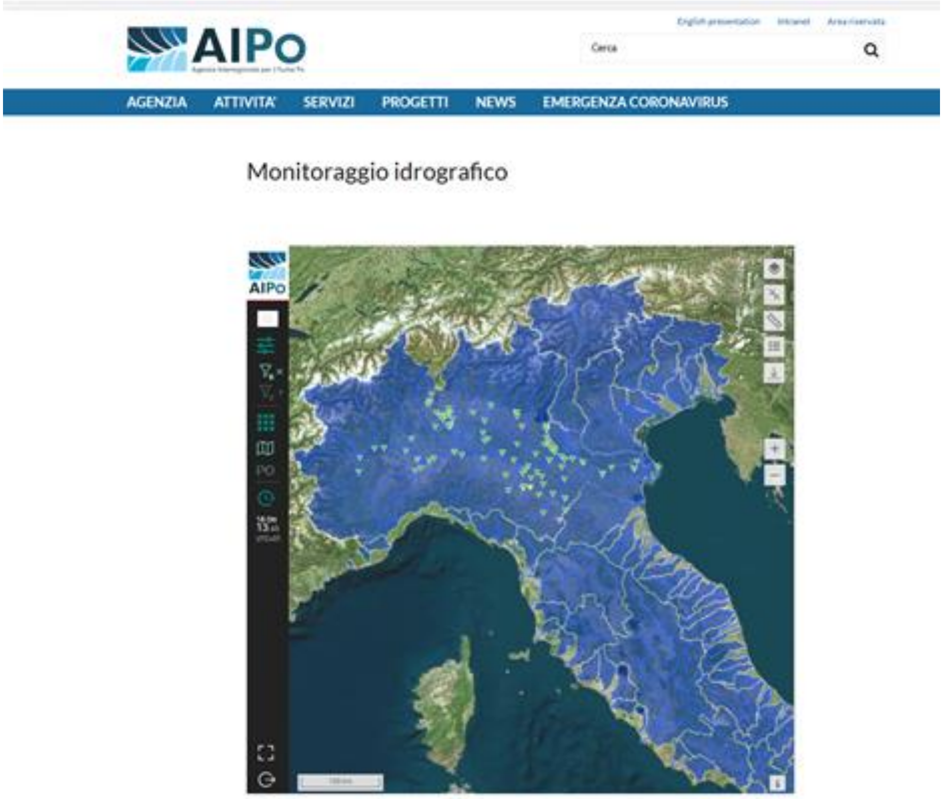


Figure 48: Snapshot of the website of the Agenzia Interregionale del Fiume Po related to the real-time hydromonitoring network

Along the main channel, the Po River is monitored by 18 stations (Figure 49) that record the water level every hour (or half-an-hour). Site specific rating curves provide the river discharges corresponding to the registered water level. Such rating curves are publicly available.

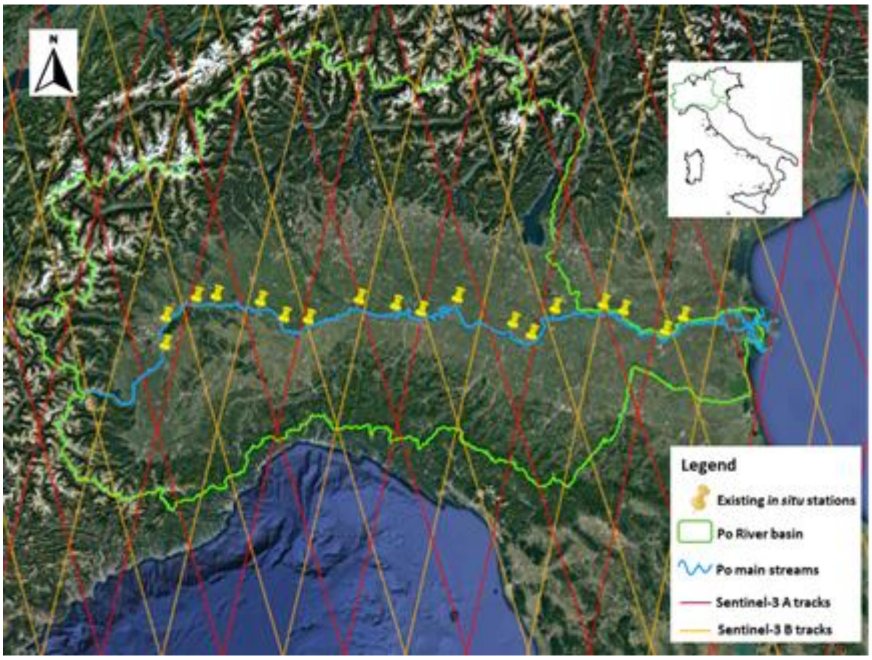


Figure 49: Location of the existing in situ stations along the main channel of the Po River

5.4.6 US network

USGS is the US national entity in charge of the maintenance of the water monitoring service in the US. It provides over 6000 in situ data of various types: water height, water discharge, water quality, ground water, etc.

All data are described and available on the web server: USGS Water Services

This site serves USGS water data via automated means using web services and extensible markup language (XML), as well as other popular media types. Services are invoked with the REST protocol. These services are designed for high fault tolerance and very high availability.

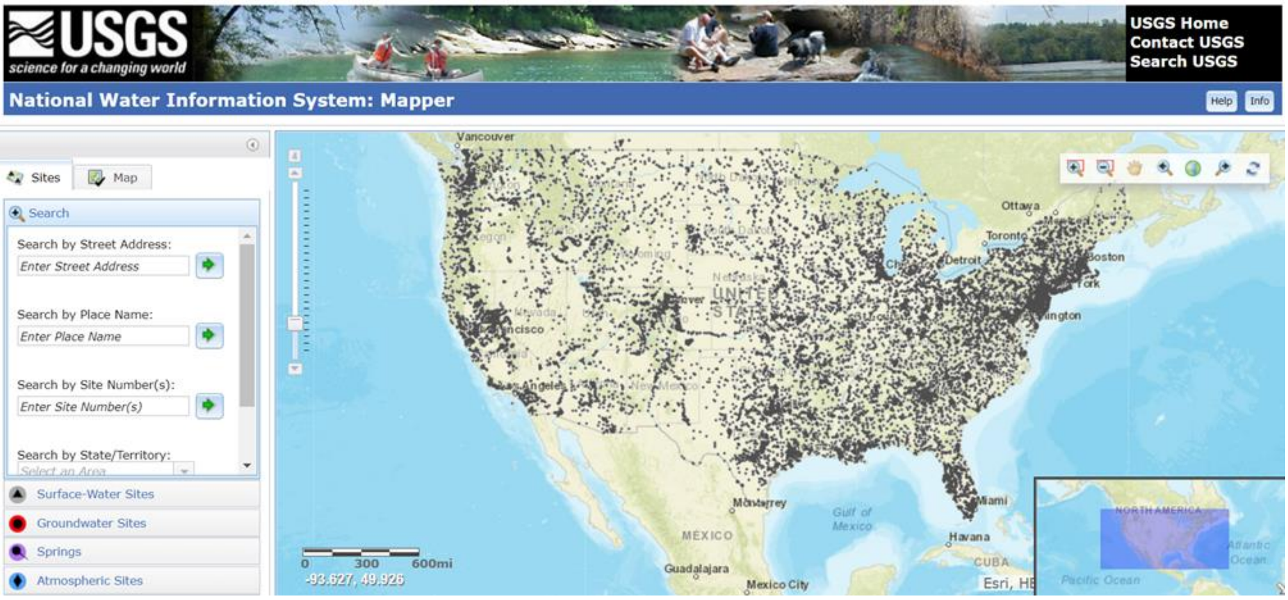


Figure 50: Snapshot of the USGS web portal for the National Water Information System

5.5 A sensor for each need

The sensor selection is strongly site dependent. It is not possible to define a standard instrumentation applicable for all Cal/Val sites (even in general for rivers, lakes, or estuaries). Instrumentation will depend on:

- the surrounding terrain and accessibility,
- existing infrastructure,
- geometry between the satellite and the water body.

It is clear that the different sensors are therefore complementary.

5.5.1 Performance analysis in a test basin

In the framework of the St3TART project, a performance analysis has been performed in a test basin in Marseille Luminy (South of France), to evaluate the accuracy of two sensors:

- The vorteX.io Micro-Station (based on LiDAR system)
- Cyclopée (based on an acoustic radar altimeter)

From April 25 to 27 2022, the St3TART hydro team performed surface roughness sensitivity tests with two different in-situ instruments used in the project (i.e., the vorteX.io micro-station and the measurement part of the Cyclopée system) in the large wind-wave tunnel of Luminy (LASIF-IOA) in Marseille. The objective was to analyse and calibrate both systems depending on the surface roughness conditions that can be found over inland waters. In the framework of the St3TART project, both instruments are currently used and will continue to be deployed under Sentinel-3 tracks to provide Fiducial Reference measurements for the Calibration and Validation activities.

During these tests, different water surface roughness conditions have been generated thanks to the large wind-wave tunnel with different wind speeds and/or swell amplitudes. The quality of the measurements already collected and compared is very encouraging, regarding the qualification of the instruments.

The Figure 4 illustrates the facility used for performing these tests.

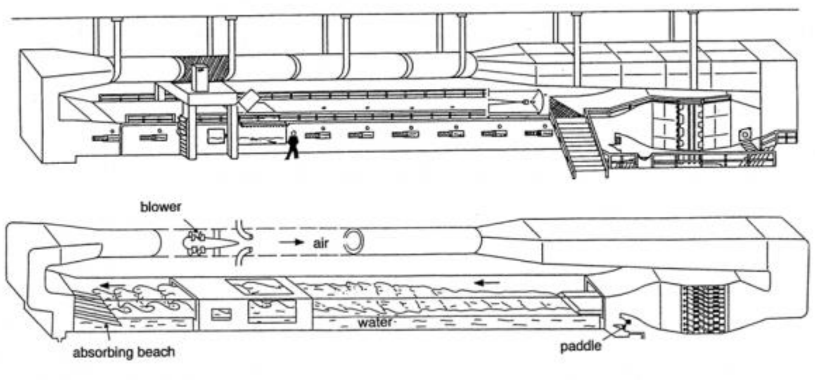


Figure 51: Schematic views of the Large Air-Sea Interaction Facility (LASIF). Credits: G. Caulliez

The first sequence of measurements was dedicated to deriving the instrument biases in calm water conditions. The standard deviation for each series of measurements (different reference heights) and for both instruments (altimeter and lidar) is below 1 mm and is shown by the error bars on Figure 52. For the lidar, the short distances (below 2 m) were not suitable for the instrument setting, leading to a high saturation level (this has been corrected by adjusting the gain for the roughness test session). On the contrary, for the altimeter, the highest distance (3.456 m) was too close to the instrument range limit (3.5 m) but the off-nadir measurements can also contribute to the increase of the bias. The mean biases are 5.8 ± 2.0 mm and 8.3 ± 4.5 mm for the altimeter and the lidar, respectively. The conclusion is that both instruments are in line at the few mm level and able to measure the calm water surface height at an absolute accuracy better than 1 cm.

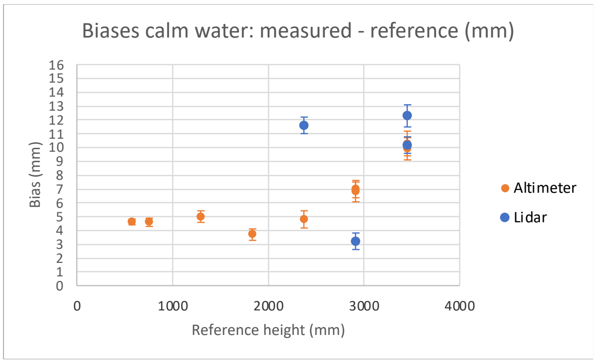


Figure 52: Biases (measured distance – theoretical distance) as a function of instrument's height. Measurements below a height of 2m are not considered for the LiDAR because they are outside the operating range

The second sequence of measurements was dedicated to deriving the instrument biases with waves. Figure 53 shows the biases for each sequence of measurement and their standard deviation. Results show that the mean biases are not significantly different from those in calm water situations. The conclusion is that both instruments are in line at the few mm level and able to measure the surface height with waves at an absolute accuracy better than 1 cm.

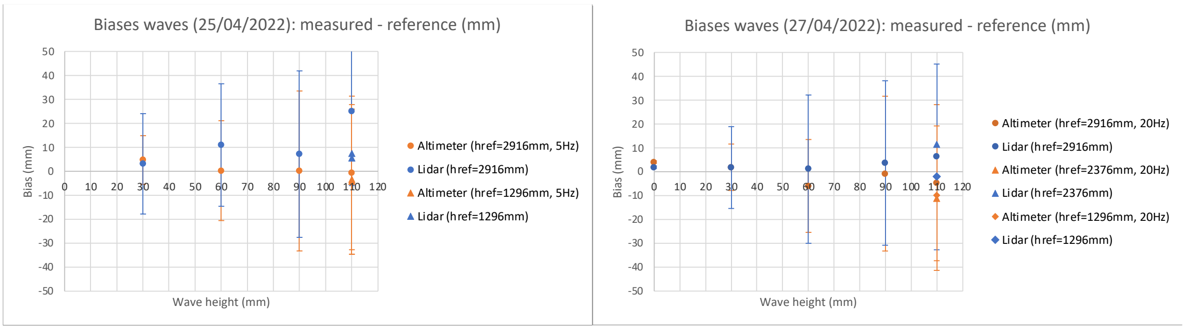


Figure 53: Biases as a function of wave height for different reference height: (left) on 25/04/2022 and (right) on 27/04/2022

The third sequence of measurements was dedicated to analysing the instrument performances with surface roughness. The surface roughness is generated by wind and the wind speed values used in this experiment were 2, 2.3, 4, 6, 8, 10 m/s that generates respectively cells with size of 70, 80, 250, 400, 500, 600 mm at the water surface.

Figure 54 shows a clear quasi linear dependency of the bias as a function of roughness size (wind speed). For the altimeter, it remains below the 10 mm level. The curve for the reference height of 3456 mm which, as already mentioned, is close to the instrument range limit (3.5 m) and it is not presented. For the lidar, it remains also at the 10 mm level. The curve for a reference height of 2376 mm is not presented: the LiDAR gain loop is failing because the instrument is not in its nominal working height (more details are given in the campaign report).

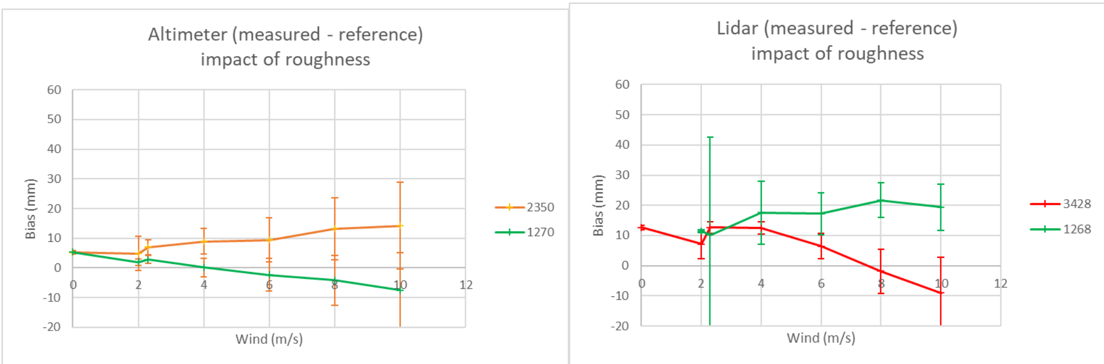


Figure 54: Impact of roughness on the water level biases: (left) altimeter and (right) lidar

In conclusion, both instruments can retrieve the water level within ~10 mm whatever the surface roughness as expected by their specifications.

These two instruments are recommended for Cal/Val activities as they are in line with the requirements. Of course, it is not possible to realise tests in a controlled basin with all instruments listed in the chapter 5. This experiment was conducted to validate that the instruments are in line with their technical sheets. In this framework, the recommendation for the project is to use sensors with a specified accuracy of 1 cm or less in their respective technical characteristics for water level measurements.

5.5.2 Comparison of all sensors

We provide in this chapter a comparison of all sensors for the operational FRM provision. The following characteristics are compared:

- Accuracy level
- Calibration needs
- Ease of deployment in the field
- Connectivity and power supply

- Ease of maintenance to ensure the operationality
- Costs

Legend:

- '++' = excellent
- '+' = good
- '-' = not good
- '--' = bad

Rank:

- A = To be preferred for operational FRM provision over inland waters
- B = To be used to complement rank "A" sensors over inland waters
- C = Not recommended for operational FRM provision over inland waters

Table 8: Comparison of the strengths and drawbacks of all sensors for an operational FRM provision

Sensor	Water level accuracy	Calibration	Ease of deployment on the field	Connectivity and power supply	Ease of maintenance	Costs	Rank
Autonomous and connected Micro-Station	cm-level	Need for GNSS	+	++	++	+	A
Pressure sensors	cm-level	Need for GNSS	+	-	+	++	A
Ultrasonic / Acoustic sensors	cm-level	Need for GNSS	+	--	+	+	A
Radar sensors	cm-level	Need for GNSS	+	--	+	+	A
GNSS buoy	cm-level	Integrated	--	-	--	-	B
Boat embedded GNSS sensors	3-4 cm	Integrated	-	No real time	--	-	B
Citizen Science	cm-level	Need for GNSS	+	++ but no regular measurements	++	++	B
Towed GNSS Carpet	cm-level	Integrated	-	No real time	--	-	B
Boat embedded GNSS and	cm-level	Integrated	-	No real time	--	-	B

acoustic sensors							
Unmanned Surface vessels	cm-level	Integrated	-	No real time	-	-	B
Unmanned Aerials vehicle	cm-level	Integrated	+	No real time	-	-	B
Airborne LiDAR	Few cm	Integrated	-	No real time	--	--	B
Limnimetric gauges	cm-level	Need for GNSS	-	--	++	++	C
Bubbler sensors	cm-level	Need for GNSS	--	-	--	+	C
GNSS-R sensors	Decimetre-level	Integrated	+	--	+	+	C
Gauge with Camera	~2 cm	Need for GNSS	-	-	+	-	C

6 Use of other satellite missions

6.1 Radar altimetry missions

With the continuous improvement of new altimetry missions, other satellites can be used to perform Cal/Val activities over inland water. A good example is the Sentinel-6A Michael Freilich mission that was launched in December 2020. This new satellite from the Copernicus program is dedicated to pursuing the objectives of the Jason-3 mission concerning the sea surface height measurements. Even if inland water monitoring is not among the main objectives of the mission, the new generation of altimeter embarked on-board (POSEIDON-4) allows the development of new methods for processing of radar altimeter waveforms over these areas [RD57].

Indeed, in the framework of the St3TART project, CNES has demonstrated the ability of Sentinel-6 to measure the longitudinal Garonne River profile in Marmande thanks to the interleaved mode used by the POSEIDON-4 delay Doppler altimeter. After a Fully Focused SAR (FFSAR) processing, the Sentinel-6 radargram is presented in Figure 55 over the Garonne River in Marmande.

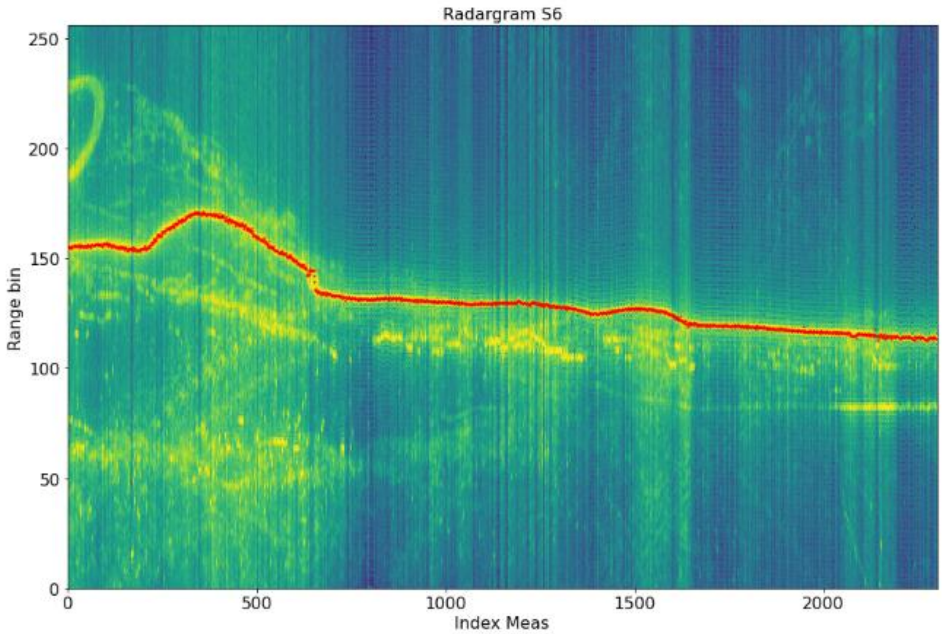


Figure 55: Sentienl-6 Fully Focused SAR (FFSAR) radargram over the Garonne River in Marmande (South of France)

Then, thanks to a specific FFSAR waveform processor developed by CNES, the water surface height of the Garonne River has been retrieved and compared to a drone campaign performed on the same area, but one day before the satellite overflight. After correction of the water level evolution during the period between the two measurements (Satellite and drone) thanks to the local Vigicrues station, and some slant range corrections, the comparison is shown in Figure 56. Figure 57 shows very small differences between the two measurements at nadir with an absolute difference of 2 cm. This comparison is a very promising usage of Sentinel-6 measurements for Cal/Val over inland waters. There will be additional drone deployments over this Cal/Val super site to confirm these first results.

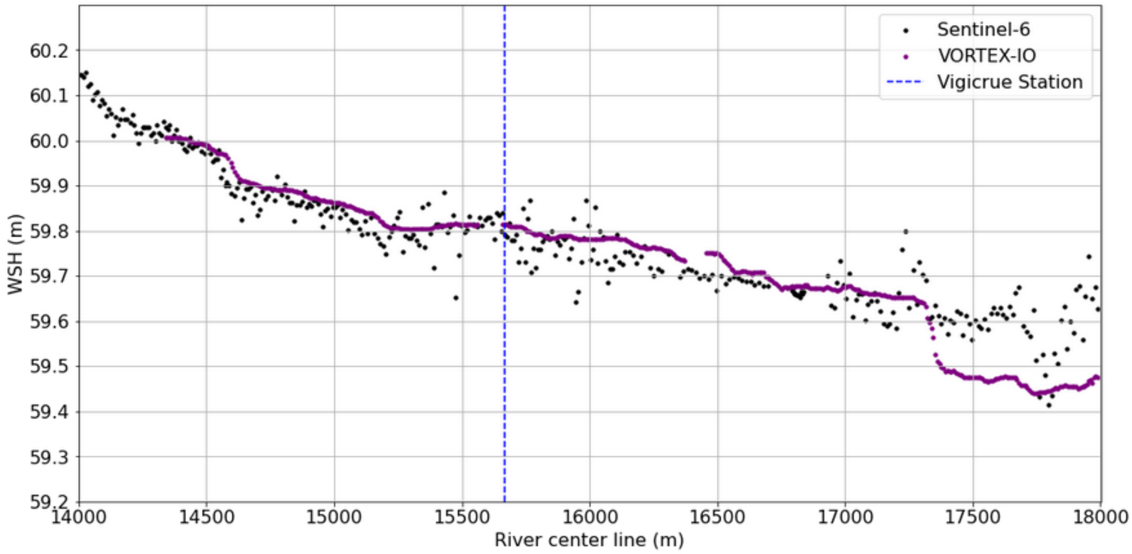


Figure 56: Comparison of the water surface height retrived from the CNES processor applied to Sentinel-6 FFSAR data and drone measurements performed one day earlier at the Marmande site of the Garonne River

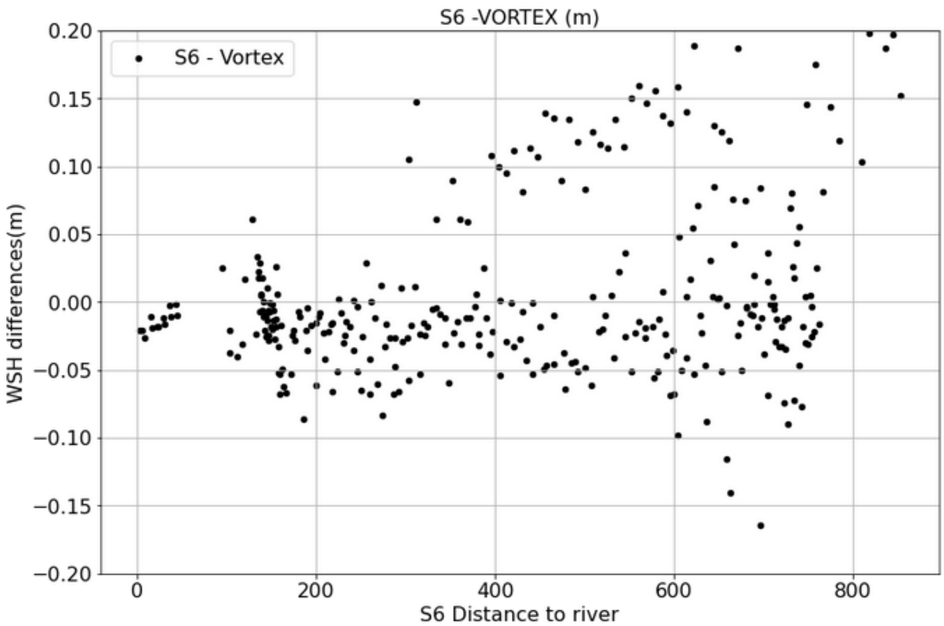


Figure 57: Differences between WSH from Sentinel-6 FFSAR and drone measurements over the Garonne River at Marmande

6.2 ICESat-2

NASA's Ice, Cloud, and Land Elevation Satellite (ICESat) mission uses laser altimetry measurements to determine the elevations of the Earth's surface. ICESat-2, which is the successor of ICESat-1, carries a sensor named Advanced Topographic Laser Altimeter System (ATLAS). This instrument uses a 532 nm (green) laser to actively map surface elevations. The laser on ATLAS is split into six beams arranged into three pairs that scribe the surface. Each beam pair consists of a strong and weak energy beam (ratio 4:1). Thus, on average the strong beam detects four times the number of photons than the weak beam [RD63]. The key advancement of ICESat-2 is that it generates individual laser footprints of nearly 14 m (in diameter) on the Earth's surface, with each footprint separated by only 70 cm, a much higher resolution and sampling than the earlier mission. One of the products, ATL13, is a specialised geophysical data product that gives the along-track and near-shore water surface height distribution within the water mask.

Even if the ICESat-2 mission is not dedicated to hydrology and knowing that no follow-on is planned to continue ATLAS measurements after the end of the mission, water elevation provided in the products can be very valuable for the

Cal/Val of Sentinel-3 measurements over inland waters. In the following part, we describe different usages of ICESat-2 measurements for Cal/Val activities.

6.2.1 Access to ICESat-2 data

They are few options available to access ICESat-2 data:

Openaltimetry is a web application allowing discovery, visualisation and downloading of ICESat and ICESat-2 data. This platform is a NASA-funded collaborative project between the Scripps Institution of Oceanography, San Diego Supercomputer Centre, National Snow and Ice Data Centre (NSIDC), and UNAVCO. Water surface heights can be visualised by selecting the ATL13 product, an area of interest, a satellite track and a specific date. All elevations are reported as orthometric heights above the WGS84 ellipsoid in metres. The selected measurements can then be exported in csv files. The data is pre-processed but the application doesn't propose enough dates.

Link: https://openaltimetry.org/data/icesat2/

In order to access additional measurements over a long period of time, it's better to use **NASA Earthdata search**; a platform developed by NASA's Earth Science Data and Information System (ESDIS) Project and supported by NSIDC DAAC (Distributed Active Archive Centre). However, an additional step is required, which is to process downloaded ATL13 files in HDF5 format (Hierarchical Data Files) to extract water surface heights in any region (Figure 58).

Link: https://search.earthdata.nasa.gov/search
Link: | National Snow and Ice Data Centre (nsidc.org)

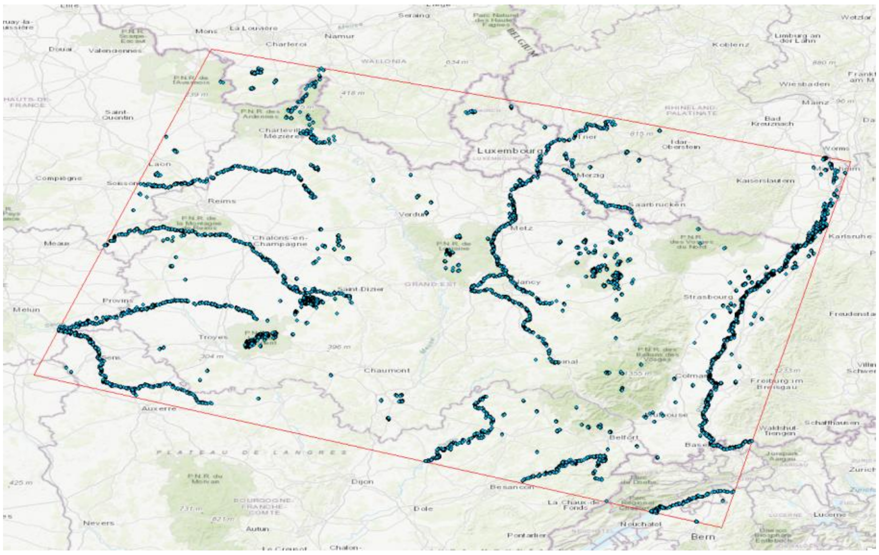


Figure 58: Locations of ICESat-2 data over Grand Est and surroundings (01/01/2019 – 29/11/2021)

For each waterbody, average water heights have been computed per available date. These measurements will be compared to in-situ data or Sentinel data. This operation was applied to 13 different lakes located in Grand Est region.

Such ICESat-2 data have also been extracted over several basins. Figure 59, Figure 60 and Figure 61 show examples of ICESat-2 data extracted from ATL13 (Oct 2018 to Dec 2021) over the Rhine, the Po and the Garonne basins. SWORD centrelines were used to define the riverbed from the centrelines and its width attributes (reaches of ~10-km length).

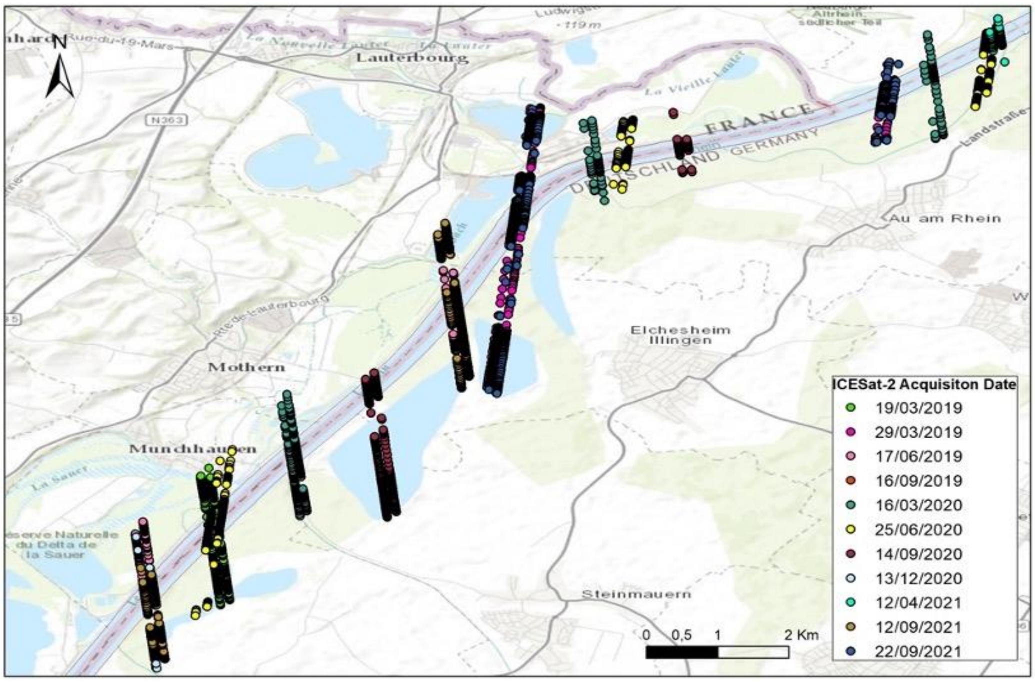


Figure 59: Example of icesat-2 data (ATL13 from Oct 2018 to Dec. 2021) over Lauterbourg area on the Rhine basin

Figure 60: Example of ICESat-2 data (ATL13 from Oct 2018 to Dec. 2021) over the Po basin

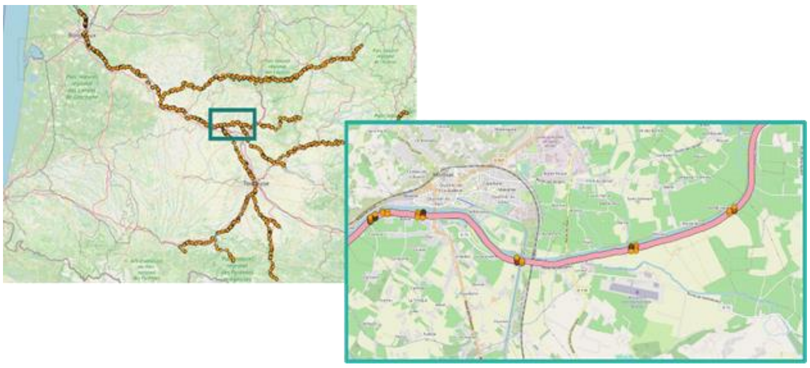


Figure 61: Example of ICESat-2 data (ATL13 from Oct 2018 to Dec. 2021) over the Garonne basin. Right panel highlights the extraction from SWORD reaches (pink polygon build from SWORD centrelines and width estimates)

6.2.2 Use of ICESat-2 to calculate the absolute referencing of existing sensors

6.2.2.1 Study area

The pond of Gondrexange (Figure 62) is in the French department of Moselle, 15 km west of Sarrebourg, with a surface of 698 ha for 14 million m3 of water. It is crossed by canals from the Marne to the Rhine and by the Houillières canal, both of which it feeds.

The pond of Gondrexange has for main bays the *Cornea of Rechicourd*, *Gros Etang*, *Cornea of Gondrexange* and *Etang du Rohrweiher* with a maximum depth of 5.5 m for an average of 2 m.

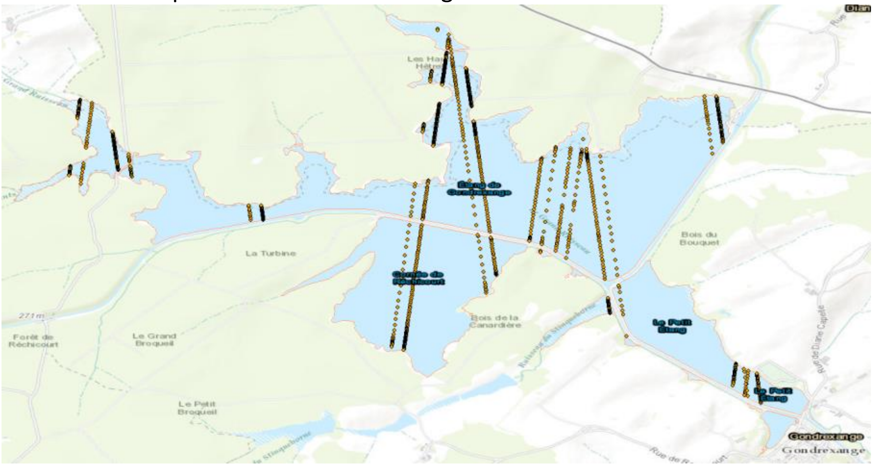


Figure 62: Location of water surface height measurements from ICESat-2 over Gondrexange (03/02/2019 – 30/07/2021)

6.2.2.2 In-situ data used in this example

One of the main in situ data provider in France is VNF (*Voies Navigables de France*), responsible for the surveillance, maintenance and management of several hydraulic structures, navigation dams, reservoir dams, etc. One of their developed tools is an online application called *Aghyre* for Hydraulic and water resource management. In our case study, water scale levels are only available over three parts of the lake (Cornea of Rechicourd, Gros Etang and Cornea of Gondrexange) with an average variation of 2 m.

6.2.2.3 Estimation of absolute reference absolute height for existing sensors

Since it is necessary to compare satellite data to in situ observations, the estimation of the absolute reference height is needed for each part which allows to transform in-situ water levels to orthometric heights.

The next diagram explains the process behind the “zero scale” level estimation for each part of the pond of Gondrexange (Figure 3).

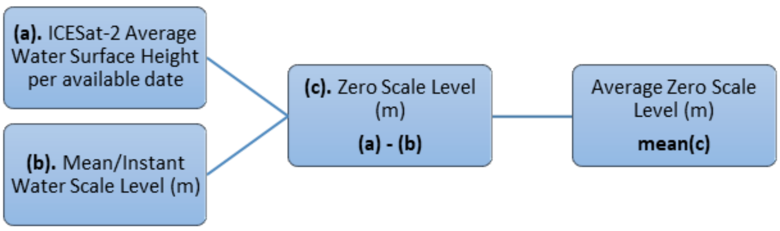


Figure 63: “Zero scale” level estimation process

Measurements and results are presented in Figure 64 and Figure 65 where the maximum absolute difference for tree parts of the pond reaches 6 cm by comparing ICESat-2 data and in-situ ellipsoidal heights.

Considering that the altimetric accuracy of ICESat-2 is centimetre level, this estimation method of the absolute reference level can be applied to any lake or pond in any region if measurements at more than two dates are available.

ICESat-2 data			VNF data				
Name	Date	Mean Height Ortho (m)	Instant Water Scale Level	Mean Water Scale Level	Level scale 0 (m)	Mean Level scale 0 (m)	max/min error (m)
Cornee de Ketzing	22/07/2020	266,2776					
Cornee de Ketzing	25/10/2018	266,4519					
Cornee de Gondrexange	02/05/2020	268,2517	4,32	4,32	263,9317	263,95	0,0144
Cornee de Gondrexange	20/07/2021	268,3452		4,39	263,9552		-0,0190
Cornee de Gondrexange	22/07/2020	267,0651	3,1	3,1	263,9651		
Cornee de Rechicourt	22/01/2020	267,7940		3,91	263,8840	263,88	0,0067
Cornee de Rechicourt	31/10/2020	266,8705		3	263,8705		-0,0067
Etang du Rohrweiher	22/07/2020	267,8815					
Etang du Rohrweiher	30/07/2021	268,6013					
Gros etang	03/02/2019	267,4424		3,51	263,9324	263,92	0,0295
Gros etang	20/07/2021	268,3694		4,42	263,9494		-0,0523
Gros etang	22/01/2020	267,2094		3,3	263,9094		
Gros etang	22/07/2020	267,0424		3,09	263,9524		
Gros etang	30/07/2021	268,1134		4,19	263,9234		
Gros etang	31/10/2020	266,9206		3,05	263,8706		
Etang du Murot	22/01/2020	267,2833					
Etang du Murot	31/10/2020	267,1294					

Figure 64: Data and results of zero scale level estimation

Figure 65: ICESat-2 and VNF water surface ellipsoidal heights

6.2.3 Use of ICESat-2 for the assessment of in-situ data quality

As detailed in paragraph 5.4.2, the French national network, the so-called SCHAPI network, is composed of several of thousands of in-situ stations with records of water surface height (WSH) on rivers. However, for georeferenced stations, the quality of the georeferencing is unknown, and might not be accurate enough to perform comparison with Sentinel-3 measurements. The use of ICESat-2 measurements, with its centimetre accuracy, is then proposed to verify the quality of the georeferencing of such stations, based on an approach similar to one explained in paragraph 6.2.2.3.

For SCHAPI stations with a levelling on local geoid convertible into ellipsoid reference (WGS84), a station is selected if there are ICESat-2 beams less than 100m away. Such constraint avoids as far as possible the impact of river slope, so that in-situ and ICESat-2 measurements could be directly compared. The nearest ICESat-2 data to the in-situ station is then selected and the two values of WSH at the same time are compared. This approach is shown for one station in the city of Castelsarrasin in Figure 66. In this example, the difference of WSH is around 1 cm, i.e. the accuracy of ICESat-2 measurements, indicating that this in-situ station is well georeferenced.

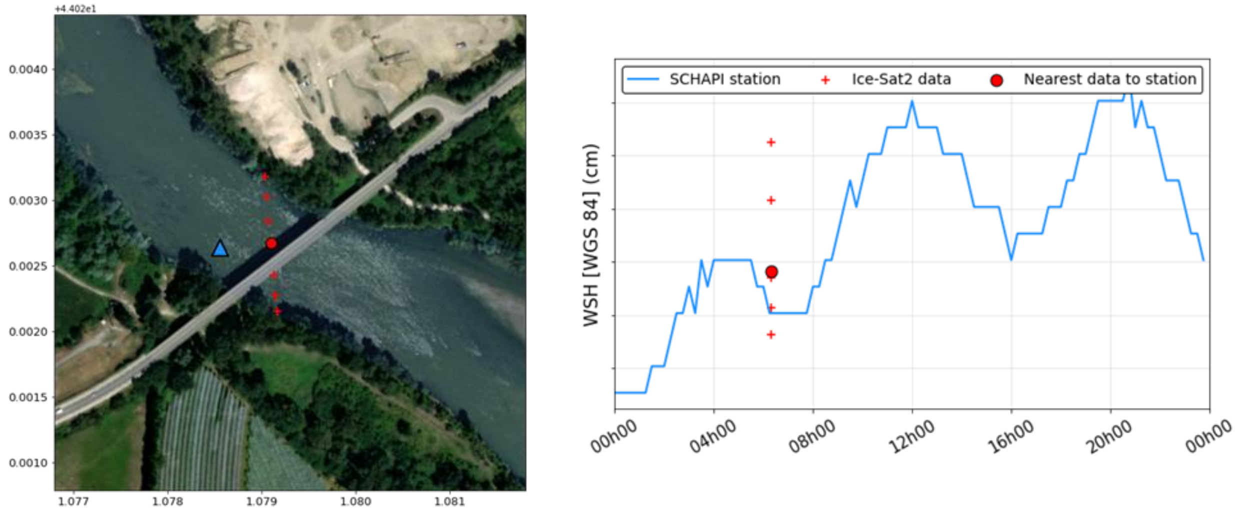


Figure 66: Left. Map of the SCHAPI station (blue triangle) and nearest ICESat-2 beam (red crosses). Right. Water Surface Height (WSH) recorded by the SCHAPI station (blue line) and ICESat-2 (red crosses)

The statistics for the 98 selected stations are represented in Figure XX. More than 70% of the stations have a difference of WSH lower than 10 cm, indicating that a large number of stations within the SCHAPI network are accurately georeferenced. The histogram in Figure 67 also shows high values of difference of WSH, which for some of them are due to complex hydrodynamic contexts. In the example in Figure XX, there is a waterfall between the SCHAPI station, and the nearest ICESat-2 beam, explaining why the difference of WSH reaches more than 80 centimetres.

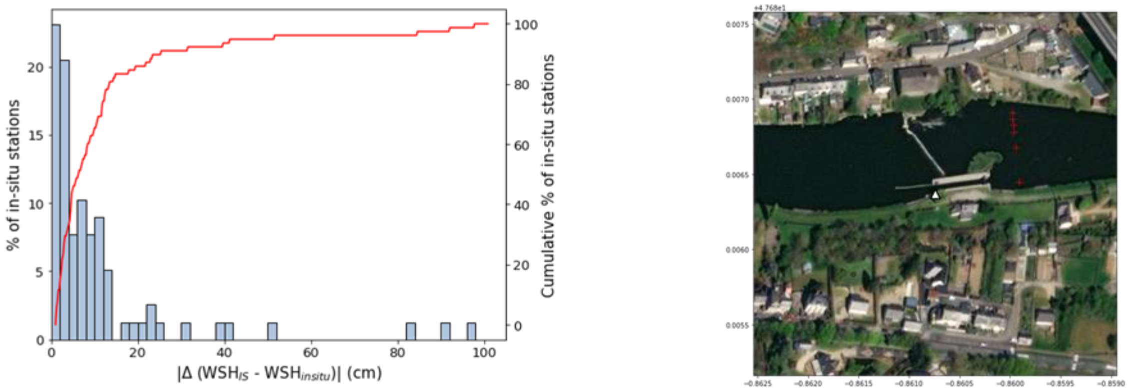


Figure 67: Left. Histogram of the difference of WSH (blue bars) and cumulative % of stations (red line). Right. Example of hydrodynamic context (waterfall) impacting the difference of WSH between SCHAPI station (white triangle) and ICESat-2 data (red crosses)

Overall, these results confirm that SCHAPI stations have most of the time an accurate levelling allowing comparison with Sentinel-3. Considering the high accuracy of ICESat-2 measurements, this approach can be also used to estimate the absolute reference height for SCHAPI stations which are not georeferenced, which would increase the number of stations that could be comparable with Sentinel-3 virtual stations. Finally, analysis of high values of difference of WSH could be promising to isolate in-situ stations where complex hydrodynamic context could have an impact on comparison with Sentinel-3 measurements.

6.2.4 Use of ICESat-2 to compute the river slope

6.2.4.1 Manual slope processing using OpenAltimetry

The first approach for slope processing was to exploit the ICESat-2 data with a manual approach, using OpenAltimetry. Slope has been processed over a site located on the Rhine River near to Lauterbourg (cf. Figure 68).

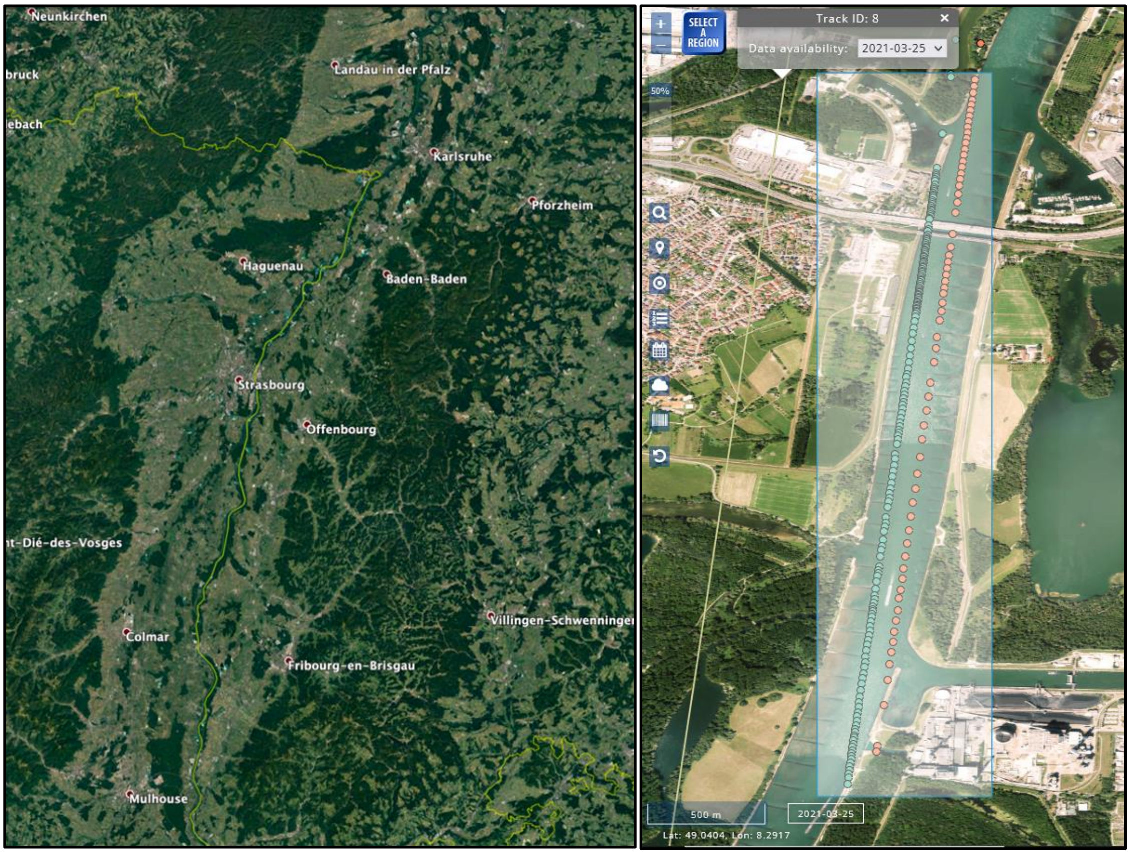


Figure 68: Map of the area

The function provided in OpenAltimetry has been used to visualize the points related to a beam. Then, the slope has been processed using the first and last elevation of each beam and the distance between them (Figure 69).

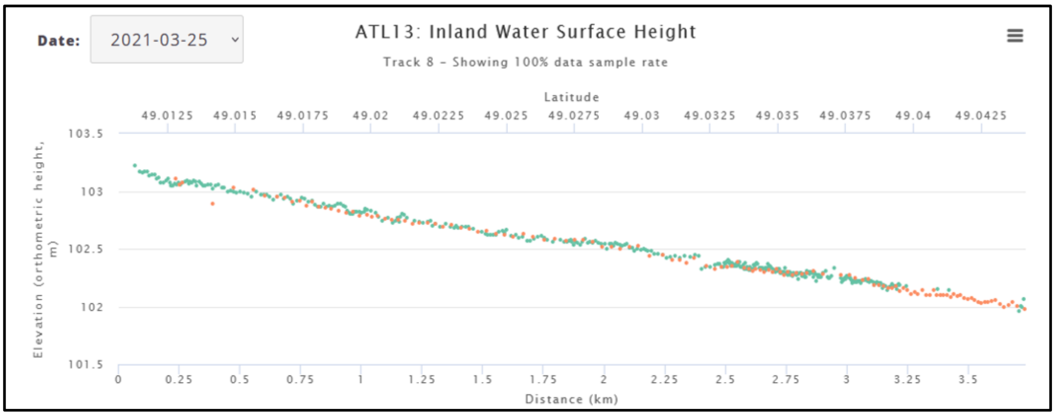


Figure 69: Elevation profile from OpenAltimetry (Strong beam in green: slope = 32.7 cm/km and weak beam in orange: slope = 31.2 cm/km)

6.2.4.2 Semi-automatic approach to process the river slope

To be more efficient and to process slopes over larger areas, a semi-automatic approach for slope processing has been implemented (cf. Figure 70).

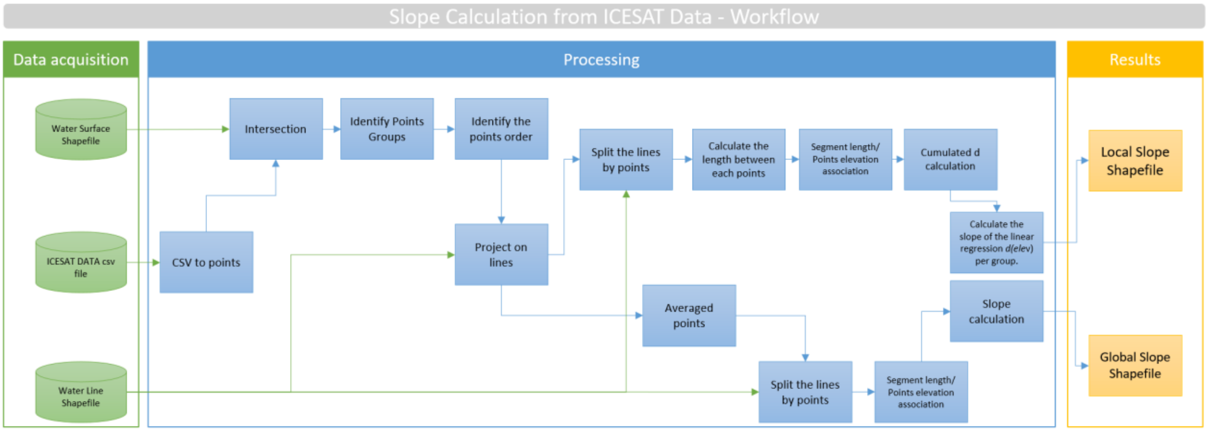


Figure 70: Workflow of the semi-automatic approach developed by SERTIT to compute the river slope from ICESat-2 data

To compute the slope with the automatic approach some inputs are needed:

- « Raw » ICESAT-2 data as provided by the OpenAltimetry website or the NASA Earthdata Search.
- Water polygon that defines the extent of the water bodies
- Water centreline (such as those of the SWORD database)

Two types of slopes are produced with this approach:

- Local slope:

  Corresponds to the slope of the linear regression of the elevation as a function of distance between each point projected on the centreline from the first projected point.

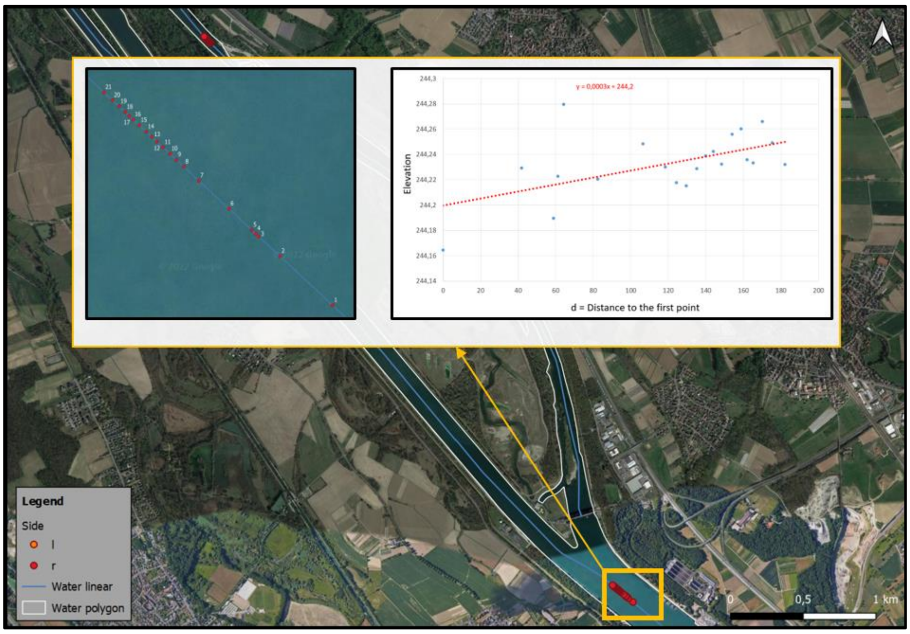


Figure 71: Local slope processing

- Global slope:

Slope between averaged points (average of the coordinates and the elevation) of each group of points. Need to have two or more than two averaged points per segments to compute a global slope.

A similar algorithm (simplified overview in Figure 72) has been developed by CLS to process river slopes from ICESat-2 data. Data can be downloaded over a given time/space domain (specific area and dates). River centrelines (SWORD for instance) are then used to extract data over inland water bodies and store them as shapefiles. For each beam, a median value of the water surface height measurements and a slope (obtained by linear regression) are computed. Then, from the river centrelines, the reach connections must be available. In other words, all the connections between the sources and the river mouth must be known. Thus, for a pass of ICESat-2, a curvilinear abscissa (distance from the river mouth) value can be associated with each of the 6 beams and used to compute the distance between two beams. As of today, this stage can be difficult to manage on the largest basins considering possible river centreline discontinuities and the amount of data (parallel computing…). Finally, a slope value can be computed for two different beams (at each ICESat-2 pass) from the difference of the water elevations median value and the beam's distance.

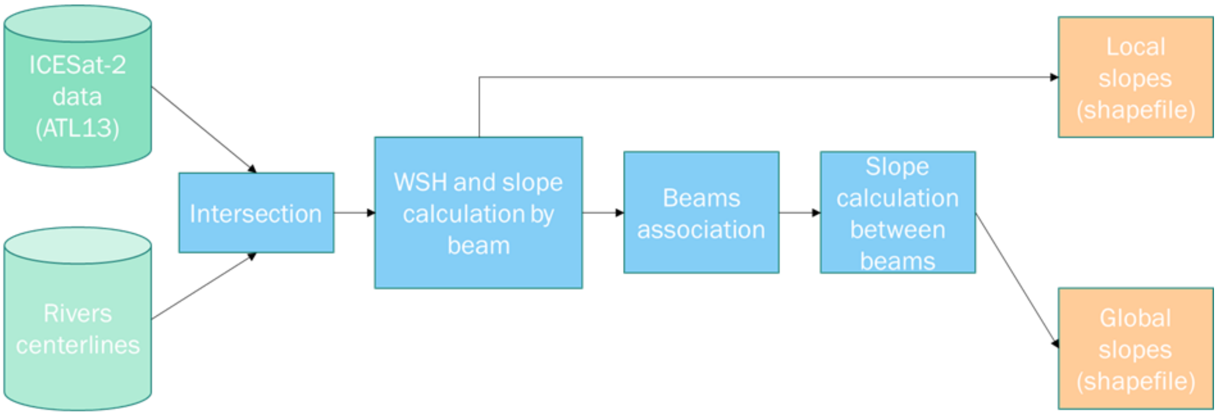


Figure 72: Overview of the river slope computation developed by CLS from ICESat-2 data over a river basin

6.2.4.3 Results of the semi-automatic approach

Local and global slope have been processed over the Rhine between Kembs and Lauterbourg for 46 dates between 01/2019 and 10/2021.

Global slope differences can be well identified at different parts of the Rhine. Figure 73 presents an example of the processed slopes between Kembs and Hartheim.

Over Old Rhine, the slope is steeper upstream of Ottmarsheim which can be explained by the presence of natural weir in the area. There are also much steeper slopes on the Old Rhine with values between 63 and 134 cm/km. On the other hand, we observe more gentle slopes on the Rhine Canal with values between 0 and 9 cm/km.

The temporal variation of the slopes must be kept in mind. However, these variations should be considered with caution for ICESat-2 data, as the segment corresponding to the slope varies over time. The segments shown in the graph below correspond to each maximum segment for different parts of the centreline.

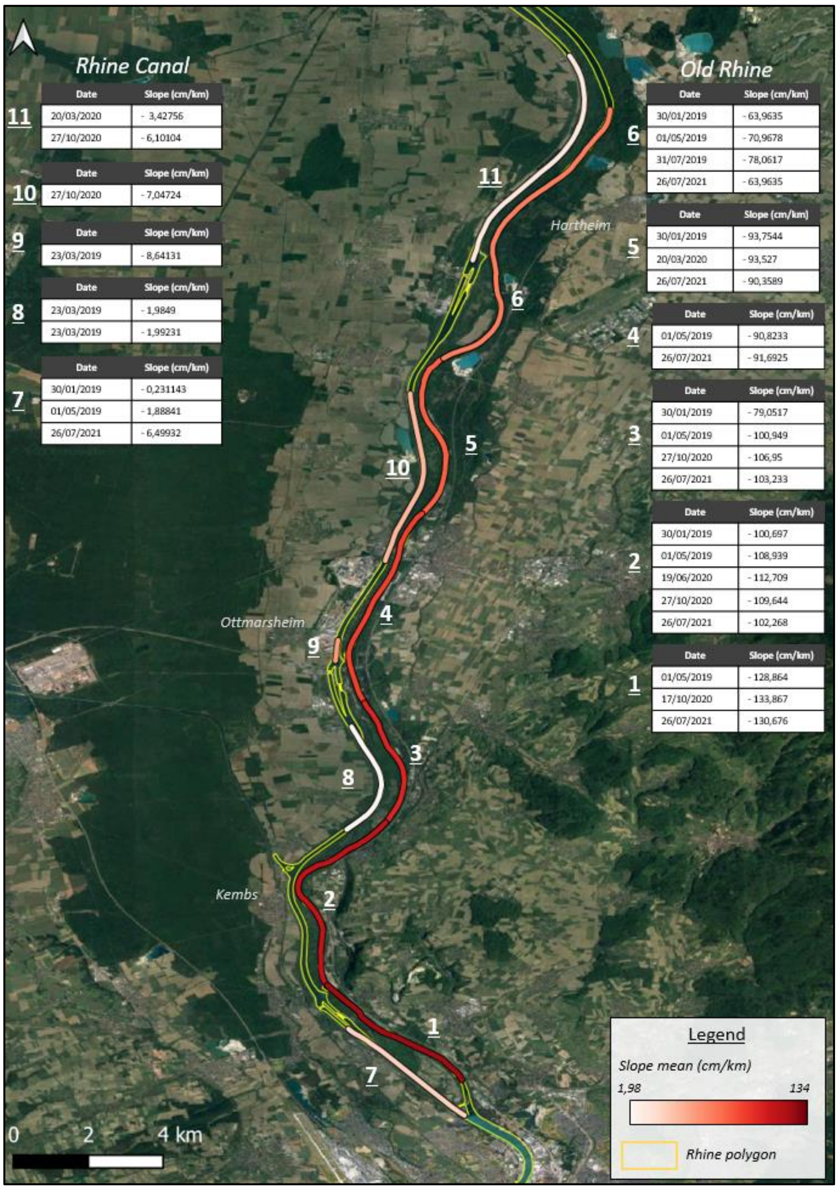


Figure 73: Global slope between Kembs and Hartheim

Such computations have been performed over different river basins by CLS. For instance, Figure 74 shows the 6 beams of a ICESat-2 pass on the Maroni (22nd Oct. 2018) and the resulting slopes calculated from the strong beams. This example will be used as a validation dataset in the following section.

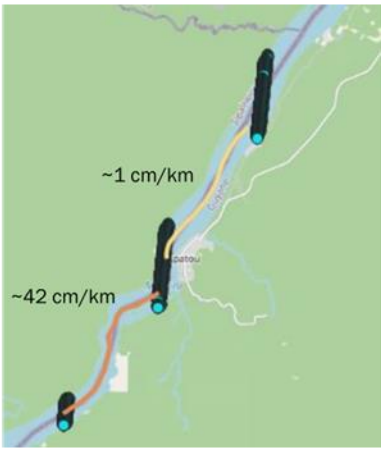


Figure 74: ICESat-2 data (dots) over the Maroni River. Centrelines from SWORD data representing slopes values

Slope computation can be represented at a basin scale. From ICESat-2 data (ATL13 Oct 2018 to Dec 2021), slopes have been calculated from different "strong" beams of each pass. Figure 75 shows the distribution of the slope measurements over the Garonne River. Values are between a few cm/km to hundreds of cm/km with a median value of about 60 cm/km. One can note a possible significant temporal variation of the slope values. Figure 76 highlights a Garonne River section from its mouth to a source. Elevation and slope profiles (with respect to the curvilinear abscissa of the river centrelines) can be seen. Such profiles can be computed for any section of a river basin defined in a specific centreline database.

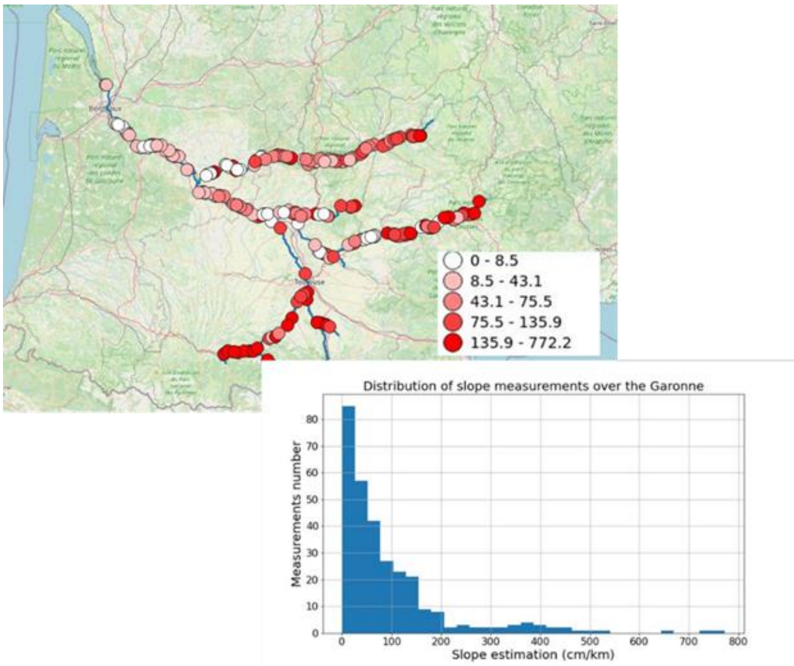


Figure 75: Slopes values (red dots in the map) and the distribution over the Garonne River from ICESat-2 data (ATL13 from Oct 2018 to Dec 2021)

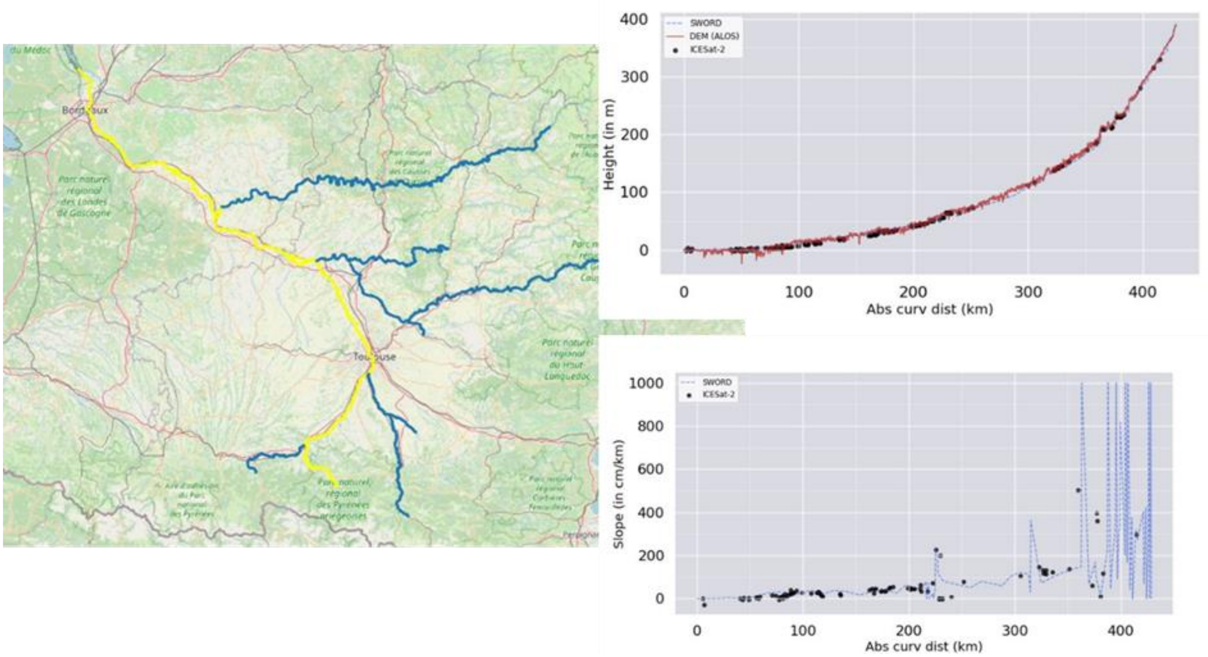


Figure 76: Height and slope measurement examples over a section of the Garonne River (yellow line, SWORD in blue)

6.2.4.4 Validation of the slopes computed from ICESat-2

A comparison between slopes derived from ICESat-2 data and in-situ slopes was carried out over different sites.

Between the *Iffezheim downstream* and *Lauterbourg stations*, roughly the same slopes are obtained with a mean absolute deviation of 5.96 cm/km, which represents an error of approximately 15%.

Between the Strasbourg downstream and Gambsheim upstream stations, errors are higher.

To be noted that in-situ segments corresponding to the slope are the same for each date, unlike the segment corresponding to the ICESat-2 slopes. The comparison has been done with each slope segment process from ICESat-2 data that intersect the in-situ segments.

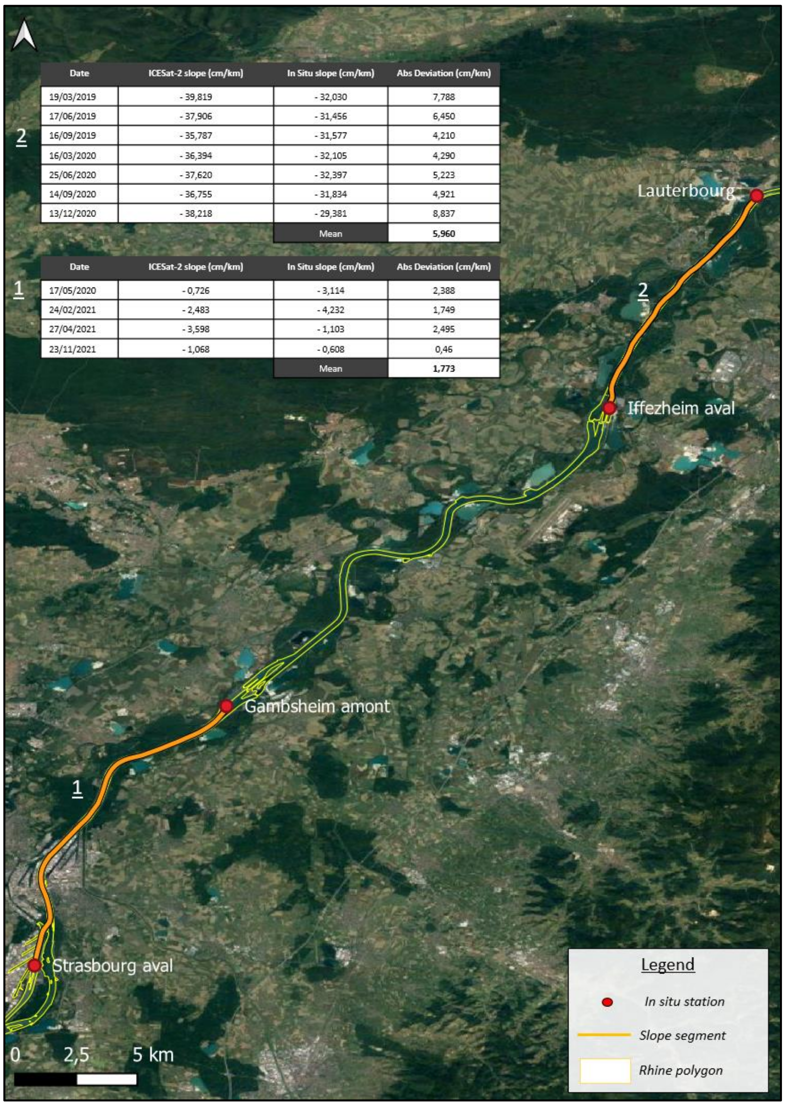
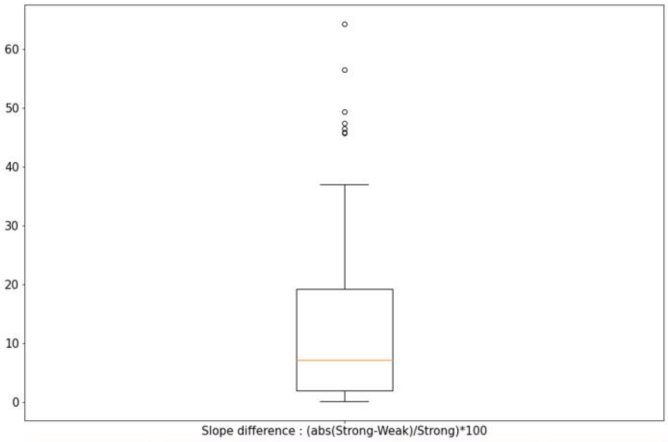


Figure 77: Global slope comparison ICESat2 / In situ

The previous example only shows results based on strong beams data, but slopes were also processed using weak beams. For this area, a difference of only 7% is noticed between the slopes obtained with the strong beam and the slopes obtained with the weak beam. This demonstrates that the weak beams can also provide meaningful values.



lower_whisker	lower_quartile	median	upper_quartile	upper_whisker
0.055891	1.911537	7.076172	19.134126	36.990408

Figure 78: Repartition of the Absolute relative deviation between weak and strong beam slopes

Comparisons have also been done using in situ campaigns over a section of the Maroni River and drone data (see section to more detailed information of such datasets). Regarding the Maroni dataset, an in-situ campaign conducted by S. Calmant and A. Paris (30th of November 2018) provided useful data for calculating the slope. Comparisons with ICESat-2 data (22nd of October 2018 using "strong beams") show a very good consistency (see Figure 79Figure 76) with differences with only a few cm/km.

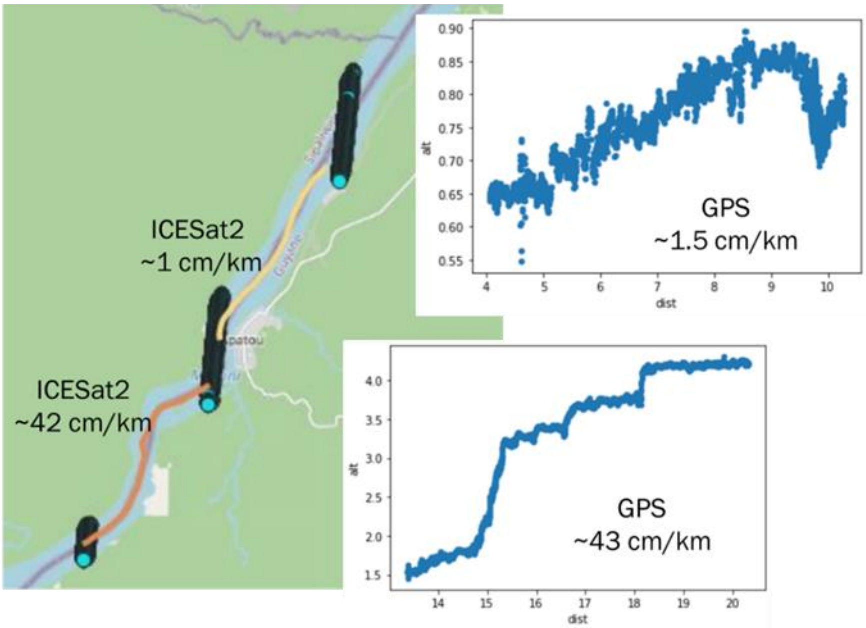


Figure 79: Slopes comparisons from ICESat-2 data (October 2018, ATL13 represented as blue dots) and in situ campaign (conducted by A. Paris in November 2018) over a section of the Maroni

Concerning the drone data, first comparisons have been made between ICESat-2 (ATL13) and drone measurements (July 2020) carried out by vorteX.io in Figure 80 and Figure 81 highlight such results over two sections of the Garonne River. The first one is a low slope section with only a few cm/km. ICESat-2 data (June 2020, ATL13 using strong beams) gives a value of about 8 cm/km. Eighteen days later (July 2020), a value of 5 cm/km is obtained by the drone measurements. However, ICESat-2 measurements so close in time to such in situ dataset are often unavailable and may cause larger differences. The second example, about 15 km upstream shows a difference of about 32 % between ICESat-2 (ATL13, 28th of March 2021) and the drone data (July 2020). In this case, the river section is steeper with a much important slope temporal variability.

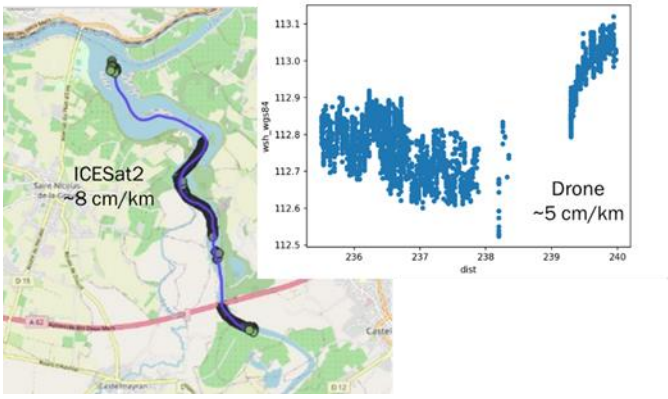


Figure 80: Slopes comparisons from ICESat-2 data (June 2020, ATL13 represented as green dots) and drone data (July 2020) over a section of the Garonne

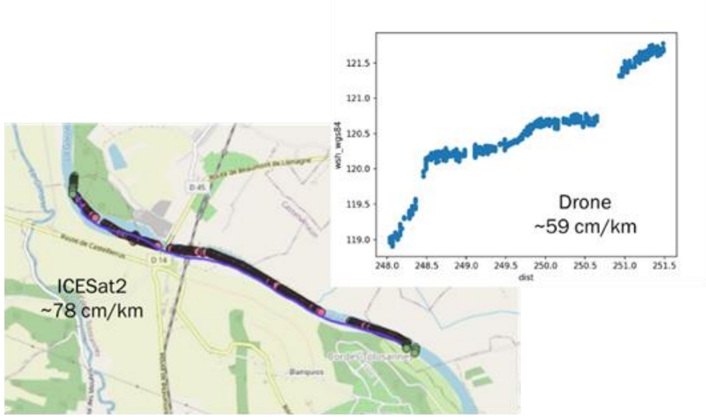


Figure 81: Slopes comparisons from ICESat-2 data (March 2021, ATL13 represented as green dots) and drone data (July 2020) over a section of the Garonne

6.3 Review of the state-of-the-art validation methodologies

Since the launch of ERS-1 and Topex/Poseidon, satellite altimetry Cal/Val activities have been largely conducted, not only over oceans, but also over inland waters, using in-situ measurements and various techniques.

Over rivers, the large majority of studies rely on existing in-situ networks and rarely deploy specific instrumentation for validating satellite altimetry data. However, in the last years and thanks to the efforts leveraged by the SWOT Cal/Val team, a lot of new knowledge on how to perform such comparisons and validation, and with which equipment, was acquired by the members of this project. The most common case for performing specific in-situ campaigns is to level existing gauges (Calmant et al. 2012 [RD39]). The idea of this levelling is to be able to use in situ gages for comparison with satellite data and to use both networks together for river management. When comparing satellite data to in-situ data, two approaches can be used: absolute comparison (Schneider et al. 2018 [RD36], Calmant et al. 2012 [RD39]) or comparison of water surface elevation anomalies (Biancamaria et al. [RD28][RD29], Halicki et al. 2022 [RD58], Tourian et al. 2016 [RD59]).

When performing absolute comparisons, the main problems encountered are:

- The proper levelling of the in-situ station
- The position of the station w. r. t. the actual satellite ground track
- The time difference between the in- situ measurement and the satellite measurement.

The main workarounds applied to tackle these problems are reperforming a new levelling, applying a slope correction based on a DEM or watershed altitude model, or performing daily averaging. We can see that the fact that the in-situ stations are not often positioned close to the altimeter tracks is a real problem that the authors must deal with and imagine innovative solutions to tackle. As the slope is variable in time and space, the correction should be leveraged out on a different basis depending on the water level.

When working with anomalies, most of the time the comparison between satellite measurements and in-situ data is performed using proxies such as a coherence analysis (computation of a Nash-Sutcliffe coefficient) or the computation of river discharge. Yet, the calculation of the anomaly for both time series can add uncertainties and must be handled carefully (same number of samples, same dates, etc.).

From the different Cal/Val activities over rivers, we can see that absolute water height is mandatory for Fiducial Reference Measurements to provide the absolute performance of Sentinel-3. The provision of absolute water elevation does not prevent from performing analysis with anomalies but enables consistent measurements between in-situ data and satellite data. In addition, we can see that it is crucial to provide in-situ measurement with the smallest possible space and time difference between the satellite measurement (actual ground track and acquisition time) and the in-situ measurement. This recommendation should be accounted for when providing Fiducial Reference Measurements. This is obviously more crucial for stations on rivers with high-frequency events than for those with a smooth hydrograph (i.e. high upstream areas).

Over lakes, specific campaigns have been conducted for many years to perform Cal/Val activities (Crétaux et al. 2011 [RD24], Crétaux et al. 2018 [RD25]) that have shown good results after improving the systems by deploying them below the satellite track, the same day as the satellite pass. Several studies have also demonstrated very good results when using existing in-situ networks over lakes (Frappart et al. [RD60], Nielsen et al [RD9]), which indicates that these existing networks are reliable enough to be used as Fiducial Reference Measurements.

The main issue over lakes is geoid errors, but it can be tackled by only considering satellite data in the vicinity of the in-situ station, or by using concurrent data (such as IceSat-2 data) to compute mean profiles over lakes.

7 FRM Protocols and Procedures

7.1 Calibration sites

7.1.1 Recommendation on calibration sites

The objective of the St3TART-FO project is to operationally produce Fiducial Reference Measurements to support validation activities and foster exploitation of the Sentinel-3 SAR altimeter Land data products over inland waters.

Based on this objective and on the complete review of altimetry Cal/Val activities over inland waters performed in this document, we provide recommendations for calibration site selection to perform the operational provision of Fiducial Reference Measurements.

7.1.1.1 Super Cal/Val sites

With the goal to perform operational FRM provision to support the Cal/Val activities, the installation of advanced in-situ instrumentation on a set of carefully selected sites is required. These sites will serve as a reference in terms of FRM quality and will allow analysis, exploration and improved understanding of Sentinel-3 measurements in different configurations of inland waters.

Super sites are a key piece in the FRM operational production:

1. It is crucial to identify sites where all the instrumentation is managed and maintained by the project to ensure the operationality without any dependency on third-party organisations. In case of a sensor failure, the sensor must be changed rapidly to meet the operational requirements

2. The selected sites must be fully instrumented to:
   a. Serve as quality reference and to reach the targeted objectives in terms of uncertainty
   b. Compute the complete known uncertainties to provide measurements with a confidence indicator allowing to evaluate the satellite performances in accordance with the mission requirements
   c. Allow further investigation of Sentinel-3 measurements with the different site characteristics (slope, water discharge, river profile, surface roughness, surface velocity, etc.) and in-situ measurements.

3. The selected sites must be representative of the different measurement configurations:
   a. Simple hydrological targets with narrow, flat, calm, and controlled water surface level. These sites will be considered as the "ideal case" where the best Sentinel-3 performances are expected.
   b. Dynamic rivers with rapid variations in the water surface level
   c. Rivers with varying slope
   d. Hydrological targets of different widths/sizes and varying surrounding complexity (swamps, flooded forest, wet margins, etc.)
   e. Different crossover geometries between the Sentinel-3 ground track and the hydrological target

It is worth noting that some criteria may not be met for all sites. All super sites must be equipped with the adapted instrumentation to measure and monitor the different site characteristics (example: river profile must be *periodically* measured and monitored if the river has a strong slope variation).

7.1.1.2 Opportunity sites

In addition to the super Cal/Val sites, it is crucial for the Cal/Val needs to compute statistical indicators on a larger number of sites to evaluate the performances of the Sentinel-3 missions over inland waters. In this framework, super sites are not dedicated to being massively deployed due to the complete instrumentation and the associated costs. We recommend taking advantage of the existing in-situ networks as opportunity sites.

With this goal, opportunity sites are existing in-situ network measurements located below a Sentinel-3 ground track and on the same hydrological target, without any hydrological feature preventing a direct comparison between the in-situ measurements and the satellite measurement.

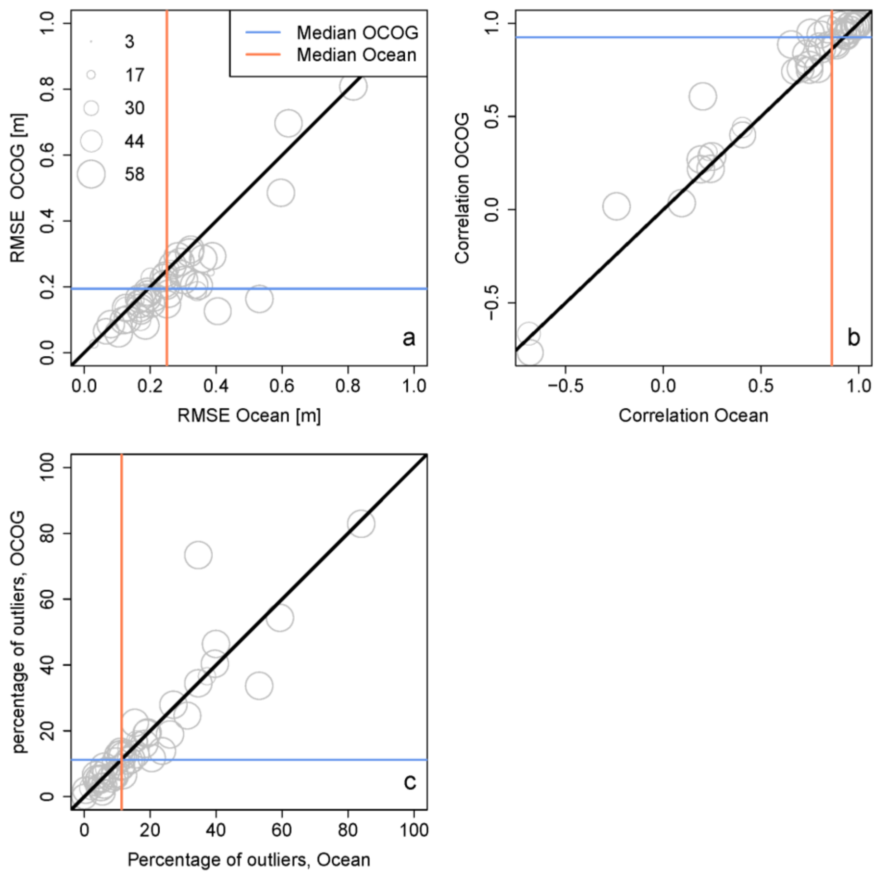
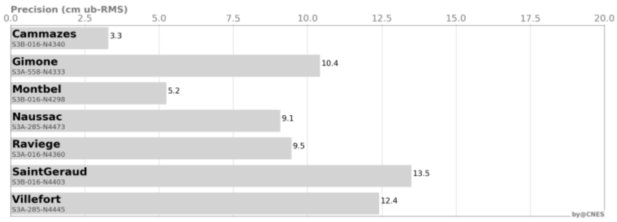


Figure 82: (From Nielsen et al., (2020)) Validation results of US Lakes study by Nielsen et al. (2020)

Gauge data from the USGS and the Canadian water office were used in a study by Nielsen et al., (2020) [RD61] to validate lake level time series based on Sentinel-3A. More than 100 US and Canadian lakes were included in the comparison, where a median RMSE of 19 cm (US) and 24 cm (Canada) was obtained for the OCOG retracker. It was also shown that the presence of lake ice has a large influence on the RMSE estimate, which is greatly improved when only including summer measurements. Figure 82 shows the validation results for the US lakes.

In a recent study Boy et al. (2021) [RD53] used data provided by EDF (Electricité De France) and by OFEV (Office Fédéral de l'Environnement, Switzerland, https://www.hydrodaten.admin.ch/) respectively over a set of Occitan lakes in the South of France and over Swiss Lakes to validate its new Sentinel-3 measurement processing called Lake Processing Prototype (LPP). They used in-situ data over a set of 7 Occitan lakes and 17 Lakes in Switzerland to validate LPP results. Lake contours have been extracted from the French CARTHAGE database for Occitan lakes and from SWOT Lake database for Swiss lakes. All Sentinel-3 measurements located over the lakes are considered in this study and directly compared to the in-situ data from local gauges after an editing step based on statistical criterion and on a threshold on the retracking MQE. Results from this study are illustrated in Figure 83.



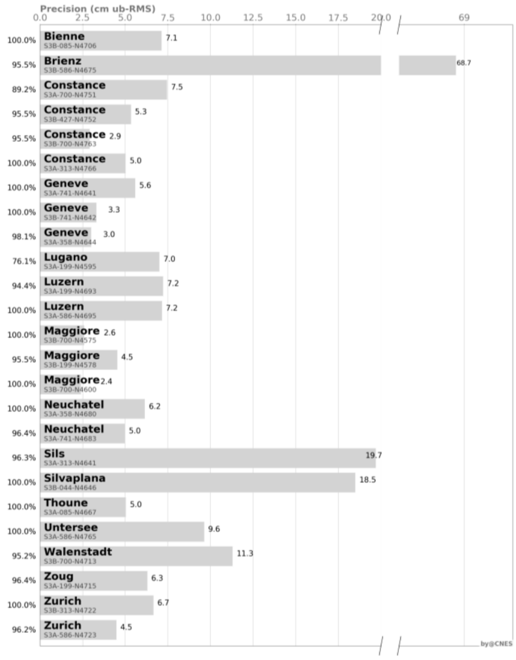


Figure 83: Left, LPP performances over Occitan lakes (ub-RMSE in cm). Right, LPP performances over Swiss lakes (ub-RMSE in cm) applying final editing strategy

These two recent studies demonstrate the reliability and quality of existing in-situ data (opportunity sites) for evaluating the performance of Sentinel-3 over lakes even if it is mandatory to analyse the quality of such opportunity sites before using them as FRM data.

Opportunity sites are then a “low cost” solution as relying on existing networks and on third party entities or organisms to manage and maintain the instrumentation.

Opportunity sites are a good way to federate communities to contribute to the Cal/Val activities of Sentinel-3 over inland waters.

It is important to note that opportunity sites cannot:

- be used to ensure operational FRM provision as the instrumentation maintenance is dependent on third-party entities
- be used to provide uncertainties as it is generally difficult to access to the specifications of each instrument installed by third party entities
- be considered as an operational provision as it can be difficult to access and automatically collect real-time data from third party entities

7.2 FRM sensor requirements for S3 LAND STM L2 product validation

Based on the sensor analysis performed in chapter 5 of this document and following the needs of the operational provision of Fiducial Reference Measurements, we provide in this chapter recommendations concerning the sensors to be used.

7.2.1 Fixed sensors

Fixed sensors must be used on each site (whatever its category: super site or opportunity site) to record time series of water level. At least one fixed sensor is required by site. A fixed sensor must be installed as close as possible (less than 1 km) from the Sentinel-3 theoretical ground track. Any type of sensor can be used from Table 8 meeting the centimetre-level accuracy requirement on the water surface level measurement and being calibrated by trustable external measurements (in-situ GNSS, moving sensor campaign, satellite measurement other than Sentinel-3…) to meet the FRM quality requirements. Sensors must be georeferenced to provide water elevation with respect to the reference ellipsoid.

7.2.1.1 Specific and additional fixed sensor requirements for super sites

In addition to these general requirements, more specific needs are mandatory from a sensor to be installed or used on a super site:

- Mandatory: 2 fixed sensors are needed at least to ensure the redundancy and the operationality of the measurements for a certain type of super sites. We perform the redundancy by instrumenting twin super sites that correspond to the same characteristics (Water body dynamic, satellite ground tracks geometry etc ...)
- Mandatory: Sensors shall be managed, operated, and maintained by the project to ensure the operationality.
- Mandatory: Sensors shall be connected to send their measurements on a daily basis at least.
- Mandatory: Uncertainty shall be provided / computed for each measurement of the sensor.
- Optional: A digital maintenance shall be performed to ensure the operationality of the measurement provision.
- Mandatory: The acquisition frequency shall be at least 1 measurement / hour but shall be configured to be adapted to the river dynamic. For example, in estuaries, the sampling must be very high (one measurement every 5 minutes or less around the satellite pass)
- Mandatory: Calibration must be performed at least once per year by trustable and calibrated external measurements (in-situ GNSS, moving sensor campaign, satellite measurement different from Sentinel-3, etc…)

7.2.2 Moving sensors

Moving sensors shall be used on super sites only if the characteristics of the site require river profile measurements or if the river slope cannot be measured by another mean (for example two fixed stations in case of a linear slope). Moving sensor measurements shall be performed several times depending on the river characteristics. Any kind of moving sensor listed in Table 8 can be used, meeting the centimetre level accuracy on the water surface level measurement.

7.3 Metrological approach to uncertainties

FRMs, as described in section 1.3, are non-satellite observations that meet the standards of QA4EO and which are helpful to the calibration and validation of satellite observations. For FRMs to meet the standards of QA4EO, they need to have traceability to a community-agreed reference (preferably SI) and have an associated quality metric (preferably a robust uncertainty budget). Several different projects have applied these principles to a wide range of satellite and non-satellite observations, and from those projects, guidelines have been established that are documented on the QA4EO website (www.qa4eo.org).

These guidelines set out 5 steps to an uncertainty budget, which are discussed in the subsections below. In this project we have begun applying these steps to some example FRMs, and one example is presented in the Roadmap Document of the St3TART project [RD64].

7.3.1 Step 1: Define the measurand and the measurement model

Defining exactly what is being measured and provided in a data set is often more difficult than it first appears. Even for an in-situ observation, the reading on the instrument (e.g., a temperature) may be different depending on how the measurement is made, i.e., on its input quantities (e.g., through a radiance measurement, or the expansion of mercury or the resistance of a thermocouple). And beyond that, the measurand of interest may be in how that reading relates to the estimate of the underlying physical phenomenon (e.g., air temperature near surface), or some representative phenomena (e.g., average air temperature in a grid cell of a model). Similarly, for a satellite observation, the measured signal, often in 'counts' needs to be converted to a physical quantity (e.g., top-of-atmosphere radiance within a spectral band). Processes such as orthorectification alter the perception of the measurand. Is an observation representing an average value within a pixel, or a peak value within a footprint? When satellite and in situ data are compared, they are likely to measure different things. For example, satellite-based measurements may relate to sea surface temperature as the top micron of the water, measured over a satellite footprint, whereas in-situ measurements may relate to sea surface temperature at a single point at a depth of a few tens of centimetres.

Furthermore, there may be questions of reference – is a range measured relative to the Earth's ellipsoid or to its geoid, for example. At higher levels of processing, where measured values are combined with models, the measurand may be even more difficult to define. However, defining the measurand is important both to describe the dataset to users and to enable clear thinking in the uncertainty budget. Sometimes, it is necessary to do separate uncertainty analysis for different linked measurands and propagate uncertainty between these steps (e.g., the uncertainty associated with the point temperature, the uncertainty associated with the average spatial cell temperature assumed from that point, and the uncertainty associated with comparing the in-situ temperature to the satellite temperature all require separate analysis).

The measurement model itself may be able to be written as an equation with an analytical function. Or it may only be defined through code, particularly if iterative processes, non-linear fitting, or machine learning techniques are part of the processing. Whether or not it can be written as an equation, the processes by which input quantities are combined to determine the measurand, is known as the measurement model. It is important to realise that there will be uncertainties associated with the form of the measurement model (whether the process it describes accurately describes reality) as well as with the input quantities that are used within it.

7.3.2 Step 2: Establish traceability with a diagram

A visual representation of how a measurement and its traceability is achieved, along with visually representing the different sources of uncertainty, are highly valuable in assessing performance. Diagrams are extremely useful mind mapping tools to help understand and communicate how a measurand is derived and to consider and share what the sources of uncertainty are. Diagrams show where terms come from and thus highlight sources of uncertainty in input quantities and in the approximations and assumptions inherent in the model.

There are different types of diagrams that can be helpful for different purposes. In this project we use a combination of uncertainty tree diagrams and more traditional processing diagrams, as well as a new concept of a comparison diagram.

7.3.3 Step 3: Evaluate each source of uncertainty and document in an effects table

After the work in step 1 to specify the measurand, and in step 2 to identify where the input quantities of the measurement model all come from, it should be possible to get a list of sources of uncertainty (also known as effects). There are several things that need to be known about each effect and FIDUCEO and GAIA-CLIM used the concept of an 'effects table' to document, systematically, the information that needs to be known about each effect.

The exact rows of an effects table will depend on the application, but there are several common requirements. This is for each source of uncertainty to identify:

- Which quantity in the measurement model it affects?
- The magnitude of the uncertainty
- The shape of the probability distribution function for the uncertainty
- How the uncertainty associated with this effect is propagated to the measurand (the sensitivity coefficient)
- The error correlation shape and scale for all 'dimensions' that are relevant both for determining the measurand and for subsequent 'higher level' processing or applications that perform averages and/or comparisons

Additionally, it is valuable to document whether the analysis in the table is mature (based on sound analysis with evidence and validated through independent comparison) or very immature (based on expert judgement) or somewhere in between.

The 'effects table' provides a common method for recording what is known about each source of uncertainty. This is valuable to think through the uncertainty analysis and for recording for long term data preservation purposes. Using effects tables that follow the documentary templates and examples given in the guidelines will lead to consistency within the community.

A core part of this methodology (central to step 3) is to consider error-correlation shape and scale in all dimensions. This requires a careful distinction between the concepts of 'uncertainty' and 'error' and an understanding of the nature of environmental observations (affected by both instrument uncertainties and natural variability) and the nature of satellite observation data processing (with different 'levels' that are often processed by different scientific communities). A full discussion of these aspects is given in the documents on the www.qa4eo.org website.

7.3.4 Step 4: Calculate the FRM and its associated uncertainty

The next step involves processing the FRM, FDR or TDP through the measurement model and determining the associated uncertainties. These uncertainties need to be propagated all the way through the entire processing chain to the measurand.

There are two ways of processing uncertainties that are described in the GUM. Uncertainties may be processed using Monte Carlo methods (as in an ensemble analysis), or through the Law of Propagation of Uncertainties (a linearized Taylor expansion often recognized as 'the square root of the sum of the squares', although when there is error correlation a full covariance matrix is needed). Monte Carlo can provide better results for non-linear models and is the often the only option where the processing cannot be written analytically (e.g., in neural networks or iterative processes), however, it is computationally expensive and does not provide easy access to the importance of different sources of uncertainty. A hybrid approach can use Monte Carlo analysis to evaluate sensitivity coefficients that are propagated through the law of propagation of uncertainties or used in look up tables.

7.3.5 Step 5: Document for different purposes

Record the information for both today's users (simplified summary information that can be readily used by others) and for the purposes of long-term data preservation (recording and documenting all the information needed for the scientific analysis to be reproducible in the future).