SWOT Project

SWOT Calibration / Validation Plan

Initial Release

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1 SWOT CALIBRATION AND VALIDATION SCOPE

This section provides an introduction to SWOT calibration and validation activities to be conducted by the Cal/Val team. This introduction provides the scope and objectives of Cal/Val work, a mid-level description of Cal/Val activities, and the organizational context of how the work will be undertaken. Additional details on the Cal/Val plan itself are given in subsequent sections.

1.1 Measurement System Overview

A description of the SWOT measurement characteristics and requirements is presented in the SWOT Mission Science Document (Fu et al., 2012) and in the SWOT Science Requirements Document (Rodríguez et al., 2016). An additional description of the SWOT science goals and expected performance is given by Durand et al (2014). In this section, we present a brief summary of the measurement system key characteristics. The SWOT mission is composed of several instruments: a dual-frequency (Ku and C-band) nadir altimeter; KaRIn, a Ka-band radar interferometer; a dual-beam water vapor radiometer (Advanced Microwave Radiometer, AMR); and, a Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) beacon, a Global Positioning System (GPS) receiver, a Laser Retroreflector Array (LRA), star trackers, and gyros, for precision orbit and attitude determination. A cartoon illustrating the SWOT measurement concept is presented in Figure 1.

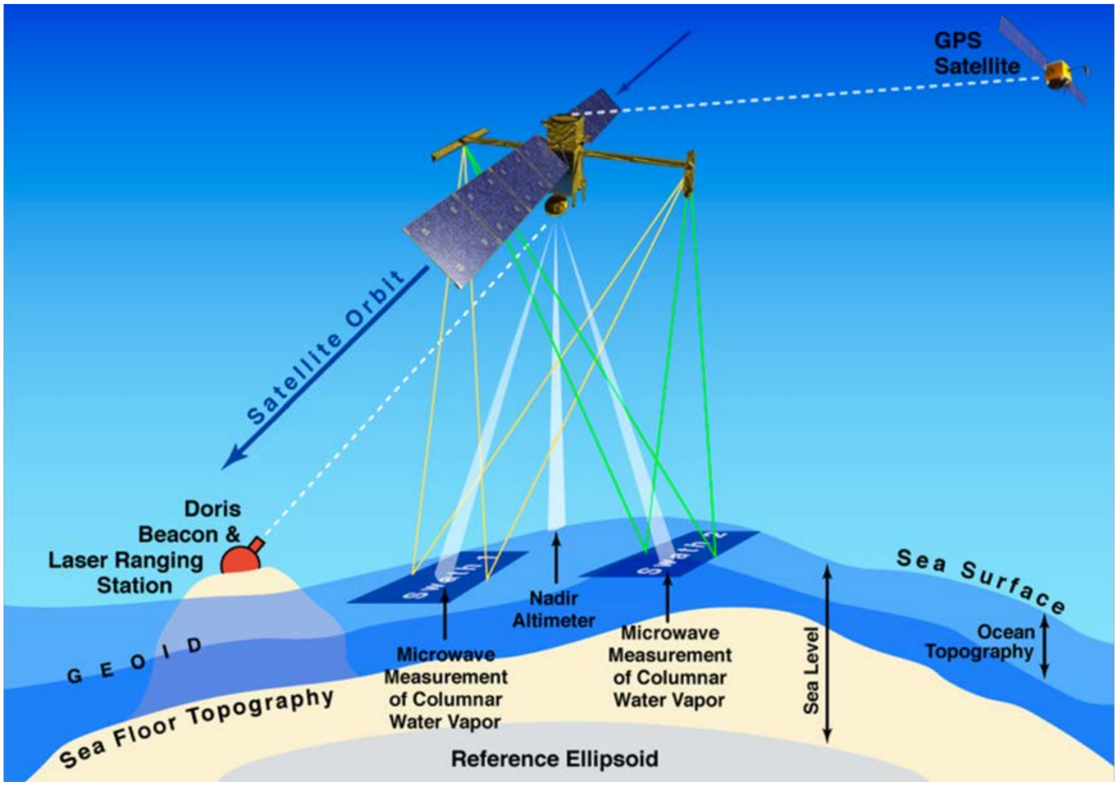


Figure 1 Measurement concept for SWOT.

Below we summarize the expected capabilities of each of these components:

1. **Nadir Altimeter**: This system is a clone of the Jason-class altimeters. It provides validation and long-wavelength measurements of sea surface height (SSH).
2. **KaRIn**: This is the main instrument for measuring high-resolution elevations for SSH and surface water measurements. It consists of a dual beam Ka-band radar interferometer, each beam providing absolute elevation measurements over a nominal 50 km swath that extends from 10 km to 60 km on either side of the altimeter nadir track. In order to meet data download limitations, the ocean data are processed onboard to a posting of 250 m. Data over land is downlinked at a higher data rate, enabling estimation of elevations with a spatial resolution, after taking azimuth looks, on the order of 25 m in the azimuth direction and 70m-10m in the range direction, depending on the cross-track distance.
3. **AMR**: This instrument is an evolution of the advanced water vapor radiometer (AMR) in the Jason-3 mission and provides estimates of wet tropospheric delays over the ocean with a resolution for its lowest frequency of about 40 km. The main difference between the AMR on SWOT and the one on Jason-3 is the presence of two beams, centered on the KaRIn swaths, rather than a single beam pointed along the nadir direction.
4. **Orbit Determination**: The SWOT mission will carry an orbit determination instrument suite very similar to the one that has been used by the Jason altimeter series (DORIS, GPS, and LRA).
5. **Attitude Determination**: SWOT includes a star-tracker near the instrument and additional gyros in the instrument suite for improved determination of the interferometric baseline.

1.2 Calibration

The scope of the SWOT calibration activities will be to conduct appropriate independent measurements to determine SWOT static system parameters used in ground processing. These parameters are expected to be constant in time. Long-term Cal/Val activities will monitor for drifts in the calibration parameters and will allow for calibration parameter updates as a contingency scenario, but the baseline Cal/Val plan assumes that the calibration parameters can be set once and will remain fixed for the duration of the mission.

Parameters used in on-board processing will be determined during the checkout and commissioning phase and are not strictly part of Cal/Val activities (See Sect. 1.5). Note that in some cases, the same parameter may take on different values for on-board processing than for ground processing. This may typically occur when a coarse estimate of the parameter is needed for on-board processing simply to avoid interferometric decorrelation, while a finer estimate of the parameter is used for ground processing in order to provide the finest possible absolute accuracy of the measurement.

Dynamic variations for some calibration-related parameters are addressed by specific operational science processing algorithms; these treated separately from the static parameters to be estimated in the calibration phase.

The full list of parameters will be given in subsequent sections, but key parameters are listed here:

Common Range Delay: This is the average of the range bias between the two KaRIn channels, and is caused by delays in the instrument that could not be calibrated prior to launch. It is the equivalent of the nadir range bias.

Differential Range Delay: This is the difference between the two KaRIn channels. Its main effect will be to cause the two channels to be miss-registered, leading to a loss of correlation and a phase bias.

Static Differential Phase: This is any residual phase between the two KaRIn channels that is static or varying very slowly (on the scale of months or years). It should not be confused with the instantaneous channel-to-channel phase that can vary due to the changes in temperature or mechanical dilations between channels; such dynamic effects are addressed via operational science algorithm processing using downlinked dynamic calibration data as well as crossover corrections.

Static Roll Angle: This is any error in knowledge of the baseline and antenna orientation after space deployment. As with the previous parameter, we only calibrate the static part and recognize that additional roll errors will be present due to uncertainties in the IMU roll estimation. In practice, one cannot differentiate between static roll and static phase biases, and an effective roll (or effective phase) will be the only parameter estimated (per swath).

Baseline Length: This parameter is expected to be known with high accuracy prior to deployment, but it will be refined during calibration (per swath). Note that the baseline length and angle can be equivalently expressed in terms of the lever arms to the antenna phase centers in the KaRIn reference frame. Dynamic variations are addressed in operational science algorithm processing through the use of crossover corrections.

Reference Point Location: The effect of location errors for the reference point in the nadir direction is (nearly) identical to a common range delay, and will be incorporated into that parameter. Errors in location in the orthogonal plane will lead to geolocation errors. It is assumed that the cross-plane location of the reference point will be known to sufficient accuracy (<10 cm), so that the effect on absolute geolocation can be neglected.

Phase Screen: Experience has shown that it is impossible in practice to match exactly the far field phase of both antennas. Differences in the phase far-field pattern, which may be caused by interaction with the baseline and spacecraft structures, will result in phase differences between the channels that varies as a function of look angle, or, equivalently, absolute phase. Unlike the other parameters, the phase screen is not a single value, but a continuous function that must be estimated across the entire swath. It has never been calibrated prior to deployment.

Absolute System Gain: Although not strictly necessary for interferometry, the absolute gain of the system is desirable if one wants to relate the wind model function derived by SWOT to that derived by other systems. However, if the model function is derived from SWOT data alone, there is no need for absolute gain calibration.

Swath-to-Swath Gain Calibration: Although each of the swaths has a different polarization, the restricted set of near-nadir incidence angles implies that a single wind model function will be sufficient for both swaths. In order for this to be the case, the gain in both channels will have to be relatively calibrated.

Antenna Pattern Relative Gain: Again, this is not required for interferometry, but is required for the estimation of mean squared slope from the decay of the cross section as a function of angle. It will be assumed that both antennas are matched sufficiently prior to launch so that this calibration is not necessary.

The nadir altimeter, on the other hand, is a simpler instrument and for the purposes of SWOT, only the altimeter range bias (and drift) needs to be calibrated against a reference constellation of altimeters and against the KaRIN interferometer range bias.

1.3 Validation

The SWOT validation activities will be divided between the projects, the SWOT science team, other agencies and foreign partners. The scope of the project responsibilities are governed by the following requirements from the SWOT Science Requirement Document (rev B):

> ***2.7.6 [Requirement] The SWOT ocean performance shall be verified by payload independent measurements or analysis during a post-launch calibration/validation period.***
>
> ***2.8.12 [Requirement] The SWOT surface water elevation shall be verified by a payload independent measurement or analysis during a post-launch validation period as well as during the mission lifetime.***
>
> ***2.8.14 [Requirement] The SWOT discharge performance shall be quantified by a payload independent measurement or analysis during a post-launch validation period as well as during the mission lifetime.***
>
> ***2.8.15 [Requirement] SWOT elevation and inundation extent performance in vegetated wetlands shall be quantified by a payload independent measurement or analysis during a post-launch validation period as well as during the mission lifetime.***
>
> ***2.6.3.a [Requirement] A Level-2 pixel cloud data product shall be produced for the surface water data. The pixel cloud data product includes:***
>
> - ***[…]***
> - ***As noted below, SWOT required performance will be*** **evaluated** ***using non-vegetated water bodies meeting the minimum size criteria set in the science requirements, i.e., water bodies with area greater than (250 m)^2 and rivers of width greater than 100 m. However, the SWOT performance will be*** **characterized** ***for non-vegetated water bodies meeting the minimum size criteria in the science goals; i.e., water bodies with area greater than (100 m)^2 and rivers of width greater than 50 m. Only non-vegetated water bodies in regions of moderate topographic relief (i.e., where layover contamination is negligible) are to be used to assess SWOT performance.***
> - ***[…]***

Although not explicitly stated in the Science Requirements Document, all mission product types described there, with the inland water bodies exceptions noted above, will be validated. That is, for the cases of significant layover, wetlands, water bodies below minimum size requirements, etc., SWOT performance will be quantified and evaluated, but the results will not be counted against the performance requirements; the science requirements are not applicable in such cases due to the exclusions explicitly defined by the requirements.

The project activities will consist of validation of the system parameters listed above, validation of the SWOT error budget, and validation of the data products released by the project. In the context of this document, "validation of the error budget" means confirming that the SWOT measurement performance, including error contributions that may be separately observable only in intermediate data, matches expectations based on the team's best understanding of the system (including instrument, spacecraft, and ground processing). On the other hand, "validation of the data products" means confirming that the SWOT measurement performance, as achieved in the data products available to users, is consistent with the SWOT science requirements. Validation will occur over a range of conditions sufficient to capture representative global performance.

The ocean science requirements impose an elevation error accuracy that is defined in the spectral domain. This should be contrasted to the traditional altimeter requirements, where the total error integrated over all scales is specified. In practice, this difference will mean that the validation of the SWOT measurements must be done over an extended test site. This is in contrast to the altimeter, where point test sites (Point Concepcion, Corsica, Bass strait) were sufficient to provide a complete validation of the measurement error budget.

Another difference with traditional altimetry is that a water body extent requirement must also be validated for fresh water bodies. In order to perform this validation, independent and simultaneous determination of water extent must be performed during performance validation.

Additional activities, beyond those covered by the requirements above may be proposed and selected by peer review under NASA ROSES or CNES TOSCA funding. These activities will not be covered by this document as they provide additional calibration and/or validation beyond that needed to meet the SWOT requirements, the subject of this document. In general, coordination between the project funded activities described here and science team calibration/validation activities will be pursued actively to reduce overlaps and utilize potential synergy between different projects.

1.4 Minimum Sites and Second Tier Sites

The SWOT project has selected a set of set of sites and instrumentation that will be the minimum needed to meet the validation requirements, and this section presents an overview of the selected minimum sites. In addition to these minimum sites, an additional set of second tier sites, or sites of opportunity, are presented which may become available through leveraging suitable foreign or agency partners, as described later in the document.

The CalVal activities for the mission will be jointly financed by the SWOT partners, with the funding for the minimal sites coming mostly from the NASA and CNES Projects, with additional contributions from Canada or other national agencies for selected sites. At this point the workshare for these activities is under finalization. NASA has included a minimal set of sites sufficient for minimum validation under its budget.

For the SWOT CalVal sites described in the following sections, there will be a minimum engagement by the CNES project for 2 main ocean CalVal sites, and 2 main hydrology sites. A number of secondary sites are also included in this document, which cover ocean and hydrology regions with different dynamics and phenomenology. The CalVal activities at these secondary in-situ CalVal sites will be accomplished with a best effort contribution from the SWOT project, combined with additional national and European finance for certain instrumentation and analyses.

1.4.1 Minimum Hydrology Sites and Requirements

In this section, we describe the minimum requirements for a comprehensive validation of SWOT hydrology objectives. The plans and sites listed here are a minimum subset of those found later in the report. More detailed plans for validating SWOT hydrology measurements and data products are described in Section 6.5, and each of the Cal/Val field sites are described in detail in Section 7.2.

The minimum validation requirements for rivers require that SWOT observations of water-surface height, slope, and inundation extent as well as discharge characterization must be validated for a range of river sizes, climate zones, and physiographic characteristics. To accomplish this objective, we have focused on a small number of so-called Tier 1 Cal/Val sites: the Willamette River (small, mid-latitude temperate, single-to-multichannel), the Tanana River (large, sub-Arctic, braided), the Connecticut River (medium-sized, mid-latitude temperate, single-channel), the lower Mississippi River (large, mid-latitude sub-tropical, single-channel), the St. Lawrence River (large, mid-latitude, single-channel), and at least one large, tropical river in South America, to be conducted in cooperation with colleagues in Brazil. In addition to the Tier 1 sites listed above, a minimum of one hundred so-called Tier 2 Cal/Val river sites will be utilized, which rely heavily on existing river gages and instrumentation.

In addition to the US sites, there will be a Tier 1 French river site that will complement the American rivers described above to add additional river types to the validation data set.

The minimum validation requirements for lakes require that SWOT observations of water surface elevation and inundation extent must be validated over a range of different lake sizes, climate zones, and physiographic characteristics. The set of lake Cal/Val Tier 1 sites include: Lake Tahoe (large, mid-latitude, moderate elevation), a group of lakes in the Sierra Nevada (small, mountainous, high elevation), a group of lakes in the Yukon Flats region (small- to medium-sized, sub-Arctic, low-topography) and a group of lakes in the Prairie Potholes region of the U.S. great plains (small- to moderate-sized, low-topography, low elevation). In addition to the sites listed above, a minimum set of fifty Tier 2 Cal/Val lake sites will be utilized.

The minimum validation requirements for inundated wetlands require that SWOT characterization of water-surface elevation and inundation extent must be validated over a range of wetland vegetation types, climate zones and physiographic characteristics. The minimum validation requirements for wetlands will be met using the following Tier 1 Cal/Val wetland sites: the Yukon Flats (boreal, sub-Arctic wetlands with sparse low-lying vegetation), the Atchafalaya Delta (subtropical, sparsely- to moderately-wooded wetlands) and the Everglades (subtropical grassland wetlands with sloped water-surface elevations).

The minimum validation requirements for tidal sites require that SWOT observations of water surface elevation, slope, and inundation extent must be validated over a range of tidal conditions. The minimum validation requirements for tidal areas will be met solely using the Connecticut River Tier 1 Cal/Val tidal site (mid-latitude, slightly- to moderately-tidal).

Finally, minimum validation of SWOT ice, rain, layover, and other flags will take place at the Tier 1 sites listed above and as many of the Tier 2 sites as possible that have adequate nearby instrumentation.

1.4.2 Ocean Minimum Validation Sites and Requirements

For scales smaller than 150 km, the main activity for validation of SWOT over the ocean concentrates on validating the SWOT error spectrum contained in the science requirements document. The validation of the *error spectrum* requires synoptic coincident measurements of SSH over a site. Airborne lidar is the primary candidate method for collecting independent truth data of absolute SSH for SWOT ocean validation at ocean wavelengths as short as 15 km. Lidar data will be collected mainly over the principal US Cal/Val site, although lidar flights over other regions will be considered as well. This approach is described further in Sect. 2. Science validation of dynamic height with in situ measurements is described in Sect. 6.4.

The selection of minimal sites is guided by the requirement to be near a SWOT cross-over during the SWOT 1-day repeat phase in order to maximize the sampling of the site, the ability to collect truth data at the site, and the size of the signal that will be present at the site. Given these requirements, three candidate sites are most promising: the Gulf Stream (7.1.2.1) site, the California Current site (7.1.2.2), and a site in the Mediterranean (7.1.2.3). The California Current site has been selected as primary because the strong currents at the Gulf Stream site may pose a problem for in situ instrumentation. Moreover, the dynamic nature of the Gulf Stream site may make SWOT anomaly resolution more difficult if unanticipated issues arise. However, the Gulf Stream site will be considered as a back-up, in case problems are identified with the California Current site during the pre-launch characterization phase. CNES will contribute a Mediterranean site (7.1.2.3), the site specifics and instrumentation remain to be confirmed, a first campaign will occur in May 2018 to test various measurements means over this site.

1.5 Overview of Cal/Val Timeline

The project mission timeline, including calibration and validation activities, is presented in Figure 2.

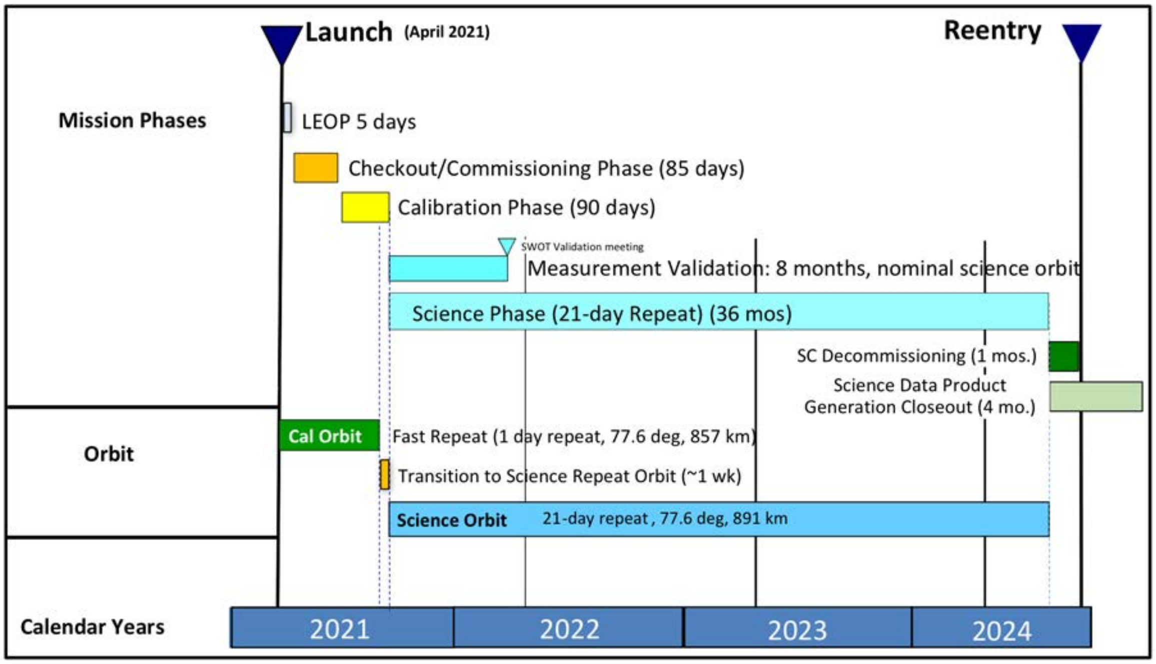


Figure 2 SWOT nominal mission timeline, including calibration and validation period.

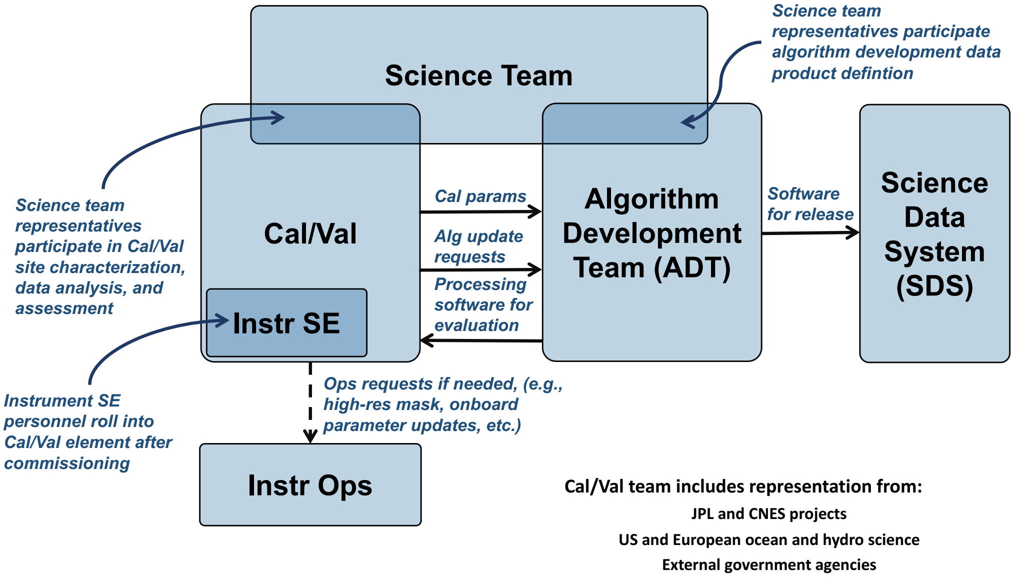
(The timeline is provided here for information only; the timeline is governed by other project documents.) The key items related to this timeline are:

1. Checkout and commissioning (85 days), where the first rough set of instrument calibration parameters will be derived. On-board parameters will be updated during the checkout and commissioning phase; science data collected from this phase may not meet SWOT performance requirements even after ground reprocessing. Validation of the On Board Processor (OBP), comparing it to a reference algorithm on the ground, also occurs during KaRIn commissioning.
2. The calibration phase (90 days), where the calibration parameters are refined and validation over selected sites takes place in the fast-sampling orbit described in Section 2.2. The calibration phase begins after on-board parameters have stabilized and been validated such that science data collected after this point can be reprocessed on the ground to achieve nominal SWOT science performance.
3. Primary validation activities to continue until the calibration and validation meeting, with low-level extended-validation activities occurring for the remainder of the mission.
4. The first calibration and validation meeting occurs approximately 1.5 years after launch. Nominal instrument and processing parameters are defined.
5. Ongoing calibration and validation activities to monitor for system drift until the end of the mission.

1.6 Team Roles and Responsibilities

During the checkout and commissioning phase, activities related to each instrument are led by the respective instrument system engineering (SE) or instrument science teams. The Cal/Val team supports these commissioning activities (for example, by deploying corner reflectors that the KaRIn SE team will use); the Cal/Val team participates in a background or "shadow" capacity. Ground algorithm testing and validation occurs during both commissioning and Cal/Val periods (see below).

Once the calibration phase begins, the Cal/Val team takes on overall leadership of calibration and validation activities going forward. At this point, the KaRIn SE team is dissolved, with key personnel from that team transition to the Cal/Val team. The Cal/Val team has responsibility for gathering external truth data for comparison to SWOT measurements, whether these data are collected via SWOT Cal/Val activities or they are produced by other existing organizations or assets. The Cal/Val team will pull these data sets together and perform the comparisons of SWOT measurements to external data. Calibration and validation are then based on these comparisons. The Cal/Val team will lead anomaly-resolution activities. Science representatives on the Cal/Val team will provide the interface to the Science Team for validation activities. These relationships are illustrated in Figure 3.



Cal/Val team includes representation from:
JPL and CNES projects
US and European ocean and hydro science
External government agencies

Figure 3. Team organization during the Cal/Val phase.

The Algorithm Development Team (ADT) will be responsible for validating the science algorithm software to the fullest practical extent using SWOT data only, without the use of external truth data. That is, the ADT is responsible for ensuring that ADT software gives self-consistent SWOT measurements that are free of gross, obvious errors. The ADT will also be responsible for fixing any ADT software problems, whether discovered using external truth data or not. The ADT will incorporate calibration parameters derived by the Cal/Val team, along with any other needed parameter or software updates, into new software releases that are delivered to the Science Data System (SDS) for operational processing.

The Cal/Val team will interact with the relevant operations team(s) for any needed on-board parameter updates if needed to resolve anomalies, though none are planned.

1.7 Document Purpose and Scope

This document serves to (1) articulate the high-level scope of planned Cal/Val activities in order to ensure coordination across project elements and external organizations; (2) define specific plans for Cal/Val activities with sufficient detail that these activities can be reconciled with project budget, schedule, and workforce plans, allowing project resources to be allocated appropriately; (3) capture detailed information regarding planned or potential Cal/Val activities in order to facilitate the transfer of knowledge across the Cal/Val team. Given the important implications of the first two objectives above, this document will be configuration controlled as a project document.

As with any plan, however, it is anticipated that this document will become less and less useful as activities move from the planning phase through the execution phase. That is, once aspects of the plan are carried out, records of these activities as they are executed supersede the plan and make those parts of the plan obsolete. Therefore, only major changes to the plan that have significant bearing on objectives (1) and (2) will trigger formal revisions to and re-release of this document. Minor changes to details may be handled informally.

2 SPECIAL PROVISIONS FOR THE CALIBRATION/VALIDATION PHASE

In this section, we provide a brief overview of special provisions that have been made to ensure the appropriate calibration and validation of SWOT.

2.1 Phase Calibration Loop and Four-Channel Raw Data Download

By implementing a calibration loop that measures the phase for a significant fraction of the transmit and receive paths for each channel, the bulk of channel phase imbalances, including all the active RF components, can be accounted for operationally. This calibration loop will significantly reduce the need for the independent calibration of channel-to-channel phase and delay variations. However, the phase calibration loop cannot include the feeds, antennas, or some of the passive elements that may introduce phase imbalance. However, since the uncalibrated paths are not active, calibration of static phase and delay differences between the channels should be sufficient to calibrate the paths not included in the phase loop.

In addition, there are provisions for downloading the raw returns from all channels for small subsets of the data. For nominal operations, only the returns from two channels (those that transmit and receive from the same antenna) are required for the estimation of elevation.

2.2 Fast Sampling Phase

The calibration of static parameters in the presence of noise and varying parameters will require averaging over multiple observations. For the nominal mission orbit, any given calibration site will be visited on average once every 11 days. Acquiring a sufficient number of samples for calibration will require a delay of the nominal mission data flow, since data processing for science products requires that the calibration variables be available. (Notice that the data collected during the calibration phase will, in all likelihood, still be valid for making science data products after the calibration constants are determined).

In order to expedite the calibration and error budget validation phases, the project has chosen to start the mission with a fast sampling phase that will significantly speed up the acquisition of the calibration of the instrument and its performance validation. This fast sampling phase uses an orbital altitude that is only slightly different than the nominal altitude such that Cal/Val results and conclusions from the fast-sampling orbit will generally carry over into the nominal orbit. Figure 4 shows sample coverage for the fast sampling orbit currently baselined by the project. The 1 day repeat time of this orbit allows much faster calibration than the 21 day repeat time of the nominal orbit.

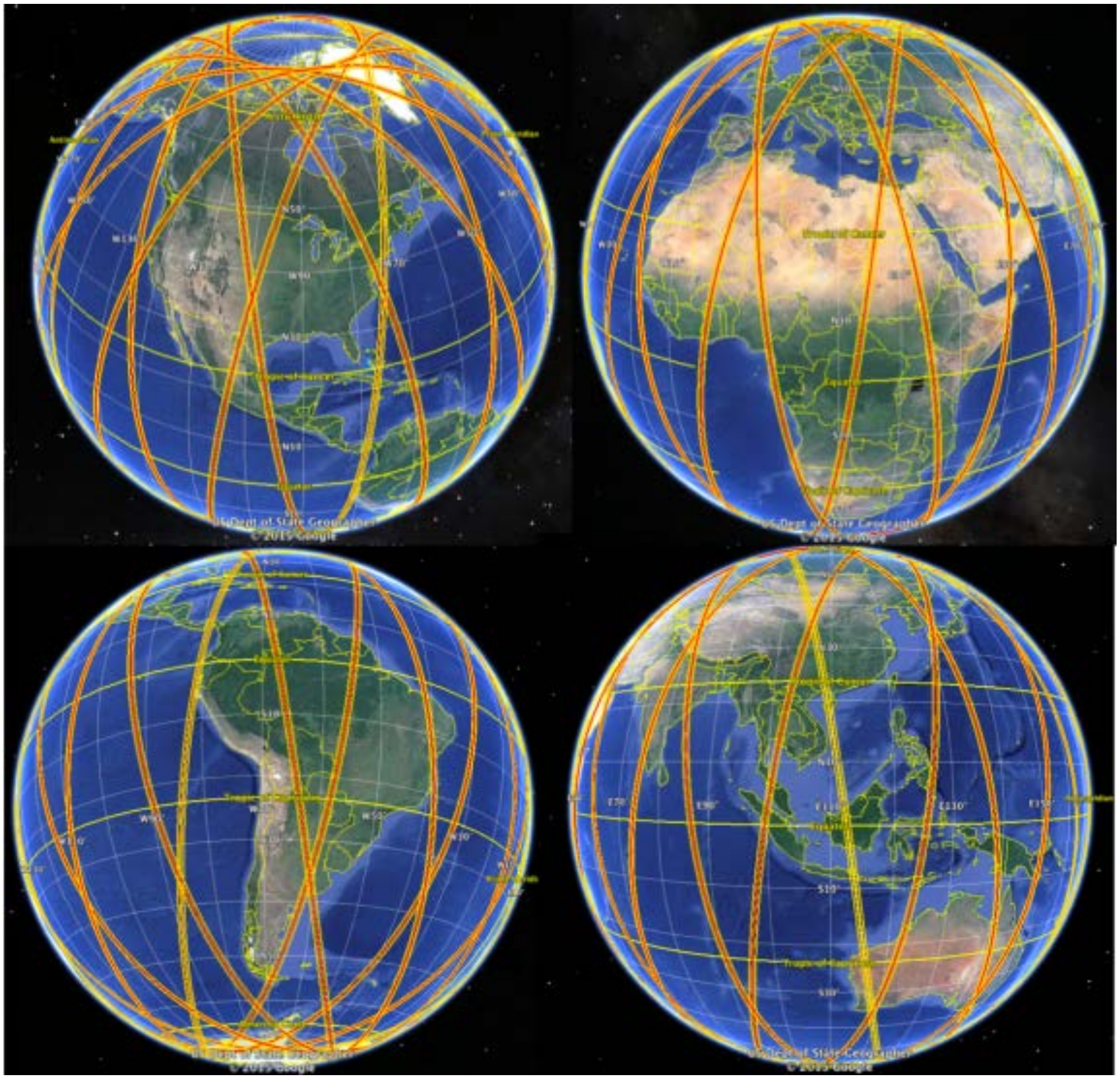


Figure 4. Fast sampling phase orbit coverage during the SWOT 1-day repeat phase.

The fast sampling phase also allows the investigation of phenomena occurring at time scales smaller than the nominal mission sampling, which will benefit the determination of ocean submesoscale decorrelation times, and the synoptic study of flood wave propagation, among others. Unfortunately, as is evident from Figure 4, the fast sampling can only be achieved at the cost of poor spatial sampling, and minimizing the calibration time to transition to the nominal mission phase will be an important consideration.

2.3 Airborne Measurements

A major challenge for the calibration and validation of SWOT is to obtain independent synoptic measurements before the phenomena being observed change significantly compared to the desired precision. One way to obtain fast synoptic measurements over large scales is to use airborne platforms. For SWOT calibration and validation, two airborne instruments are currently planned: AirSWOT, a Ka-band radar interferometer developed under NASA technology funding and currently funded and operated by the US SWOT project; and MASS, a lidar system developed by K. Melville, Scripps Institution of Oceanography (SIO), a SWOT science team member (Melville et al., 2016).

Note that AirSWOT had been originally planned for both ocean and hydrology Cal/Val. However, the ocean performance of AirSWOT was found to be inadequate for ocean Cal/Val due to wave-bunching effects that had not been anticipated. AirSWOT is therefore no longer planned for ocean Cal/Val, although it is still planned for hydrology Cal/Val and other potential pre-launch phenomenology and risk mitigation purposes. Note that the effects of wave bunching on SWOT are small and have been incorporated into the SWOT mission performance error budget (D-79084 rev A). Materials from an independent review of the AirSWOT ocean issues can be found in SWOT Docushare collection 222168.

2.3.1 AirSWOT

At the core of the AirSWOT payload is a Ka-band interferometric radar (KaSPAR, Ka-band SWOT Phenomenology Airborne Radar), whose main characteristics are given in Table 1. AirSWOT radar data are collected over an inner swath that covers SWOT-like incidence angles and an outer swath that can map up to approximately 20-30° incidence angles, depending on surface reflectivity and aircraft attitude. AirSWOT radar data generally have finer intrinsic spatial resolution than SWOT. AirSWOT height accuracies depend on a number of factors but are generally comparable to expected SWOT performance (at an equivalent posting) for hydrology targets. AirSWOT flies on a NASA B-200 Super King Air aircraft operated by Armstrong Flight Research Center.

Table 1 AirSWOT Instrument Characteristics

Parameter	Value	Comments
Number of antennas	5	Nominally used for 2 cross-track and 2 along-track interferometry swaths
Polarization	V-pol	To enhance SNR at far range
Range bandwidths	80MHz/400MHz	80 MHz for wide swath, 400 MHz for narrow swath
Swaths	4 km/500 m	
Typical azimuth resolution	3m-5m	Includes >30 azimuth looks
Transmit Power	100W	
Platform altitude	8000 m	

To provide longer wavelength corrections and positioning, the AirSWOT package includes a state of the art Inertial Motion Unit (IMU), including a high precision gyroscope coupled to a GPS receiver.

The final component of the AirSWOT payload is a color-infrared camera with pixel resolution and geolocation accuracy <10 m and a swath on the same order as the AirSWOT swath. This camera can be used to validate the SWOT water body delineation measurements.

As of January 2018, AirSWOT outer-swath height measurements have demonstrated performance that is suitable for hydrology Cal/Val. Inner-swath performance validation has been hampered by instabilities in the AirSWOT antenna hardware, but plans to exploit AirSWOT inner-swath data to the extent possible remain in place. It should be noted, however, that Cal/Val does explicitly rely on any particular level of inner-swath performance.

In the pre-launch timeframe, the AirSWOT team will continue to make improvements to AirSWOT ground processing software in order to improve the efficiency with which data are processed, making the processing less manually intensive and more robust. Additional pre-launch AirSWOT analyses will also support phenomenology investigations that are shared between Cal/Val, ADT, and Science Team efforts.

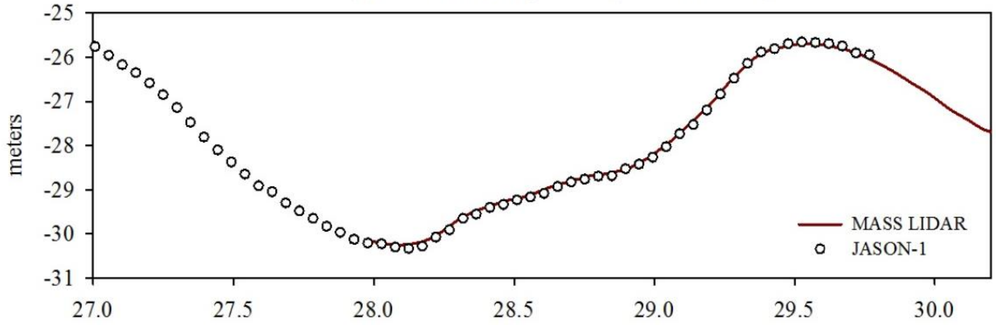
2.3.2 MASS Lidar

A description of the full Modular Aerial Sensing System (MASS) is given by Melville et al. (2016): "The core of the system for ocean wave and sea surface height (SSH) measurements is a Q680i waveform scanning lidar (Riegl, Austria) which has a maximum pulse repetition rate of 400 kHz, a maximum ±30° raster scan rate of 200Hz, and has been used at altitudes of up to 1500 m with good returns for surface-wave measurements. The theoretical swath width over water is typically proportional to the altitude of the aircraft, and its effective width is also dependent on the wind speed and sea state." The system also includes visible, infrared, and hyperspectral cameras as well as a GPS/IMU system. As of January 2018, the MASS system has been mainly flown on a Partenavia P68 aircraft.

MASS lidar SSH measurements will provide direct measurements of the absolute SSH, which is the fundamental physical quantity SWOT will measure. The MASS SSH measurements therefore provide a means of direct validation of SWOT performance in terms of both error budget and data product validation. Additionally, MASS flight patterns that cross the SWOT track can validate the 2-D nature of the SWOT measurements, which is a new aspect of SWOT compared with traditional nadir altimetry. These data can be used for troubleshooting and anomaly resolution as well as SWOT phase screen calibration. MASS measurements of directional wave spectra will allow for validation of SWOT significant wave height (SWH) estimates and related phenomenology. Furthermore, MASS sea surface temperature measurements will provide additional insights into the phenomenology of SWOT observations.

The MASS SSH measurements have been validated against the Jason-1 altimeter and have shown good agreement (see Figure 5) for the large (>150km) wavelengths that Jason-1 can resolve. In addition to the lidar, the MASS system also has an infrared camera, a hyperspectral camera, a video camera, and a high-precision coupled IMU/GPS system.

(a) Sea Surface Height SSH (WGS84, meters)



(b) Sea Surface Height Anomaly SSHA (WGS84, meters)

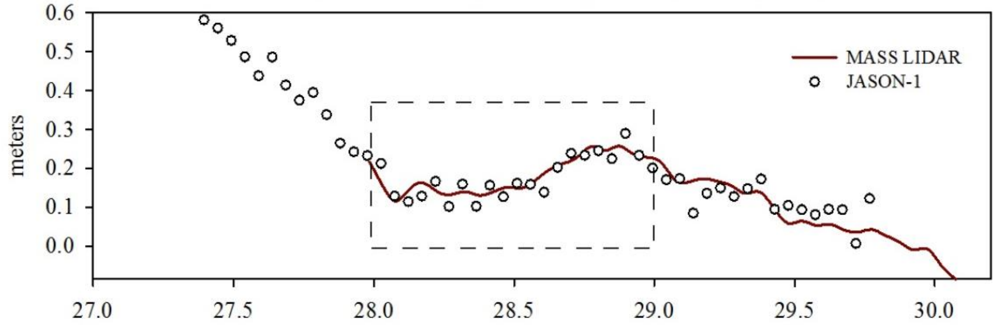


Figure 5. (Upper panel) Height above the ellipsoid measured by MASS and Jason-1. (Lower panel) Same as above, but after subtracting the mean sea surface.

Validation of the noise floor and the height error spectrum of the MASS system at short wavelengths has been demonstrated by a 2016 flight over the Algodones Dunes (see Figure 6). In this experiment, the aircraft was flown back and forth over many repeating, reciprocal passes over a desert dune field. Various fractions of the lidar returns were discarded to simulate the difference in albedo between the dune field and an ocean surface. The dune field was chosen over a real ocean target for this experiment in order to ensure that the surface did not change significantly over the time of the flight. The high-spatial-frequency noise floor of the MASS measurements meets SWOT Cal/Val needs, especially considering that a significant portion of the height error in Figure 6 is attributable to horizontal errors over the steep dunes; such errors would not occur over the ocean because ocean waves have much shallower slopes.

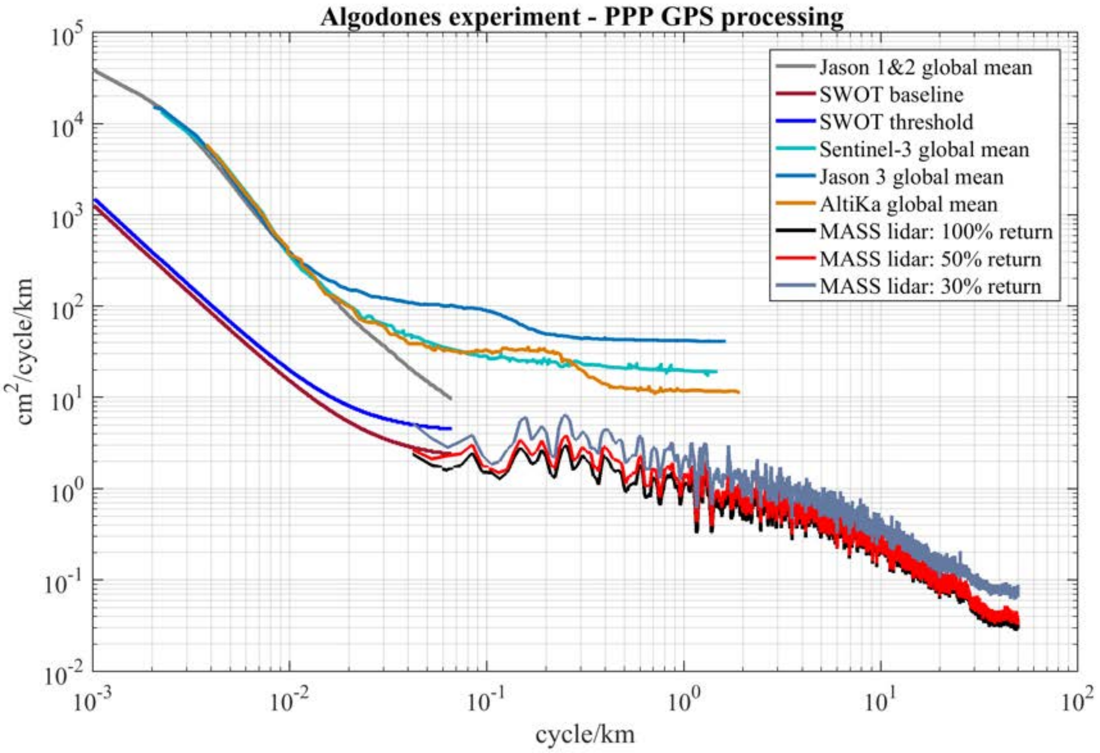


Figure 6. MASS lidar height error spectra (black, red, gray-blue curves) obtained over the Algodones dunes, with the SWOT ocean requirements and typical nadir altimetry signal levels overlaid.

Despite the encouraging results from the MASS system described above, however, the system cannot be considered fully validated and ready for SWOT ocean Cal/Val purposes because the system has not yet demonstrated suitable height error spectral performance in the range of ocean wavelengths from 15-150 km, which is key for SWOT. Spectra over this range have been generated from previous MASS experiments over the ocean, but they have generally been inconclusive, usually due to lack of independent truth data with appropriate spatial resolution for comparison. The range of the P68 aircraft is also too limited to practically support the selected ocean Cal/Val sites.

This lack of independent data for comparison poses the main difficulty in validating the MASS height error spectral performance to the shortest length scales. Ocean validation of the MASS system is therefore perhaps best accomplished through an examination of self-consistency of the MASS system's own SSH measurements acquired on repeating, reciprocal passes. This approach is difficult with the current P68 aircraft, however, because the relatively short range and endurance of the P68 limit the number of passes that can be collected at suitable length scales. The low speed of the P68 also implies longer times between repeating passes and hence greater temporal decorrelation of the ocean surface between observations. The limited range of the aircraft also does not allow it to get far from shore, where tidal variations are better modeled and are consequently more readily removed from the data. For Cal/Val, access to the crossover diamonds also requires greater aircraft range.

Note that temporal changes in SSH over the time of an aircraft flight (typically around 5 hr, but possibly longer or shorter depending on aircraft type) are problematic not only for MASS validation, but also for SWOT Cal/Val as well. If the ocean changes appreciably over the time of the aircraft flight, only the airborne data collected close enough in time to the nearly instantaneous SWOT overflight will be useful. (It would be neither logistically nor programmatically feasible to fly the aircraft many, many times to collect only a single useful flight line on each sortie.)

Because of the limitations posed by P68 aircraft, the current plan is to move the MASS system to a faster, longer-range aircraft. A NASA P-3 Orion aircraft operated by Wallops Flight Facility is currently baselined, though other P-3 options are available. An extended-range Twin Otter aircraft with lower speed than the P-3 is also possible as a deeper fallback option. The MASS system will be integrated onto the new aircraft and validated during an ocean experiment at the primary (California) ocean Cal/Val site in the pre-launch timeframe. This campaign will validate the MASS system as intended for SWOT Cal/Val and demonstrate readiness for Cal/Val operations by addressing the following objectives:

1. Demonstrate suitable height spectral error from the MASS system over the ocean at ocean wavelengths from 15-150 km. This demonstration will encompass the performance of the MASS system itself, logistical and operational constraints (including weather, aircraft availability, airspace availability, etc.), and the spatio-temporal variability of the ocean surface itself.
2. Characterize the spatial and temporal variability of the ocean at the primary Cal/Val site in order to help in the design of flight patterns and sampling approaches best suited for SWOT Cal/Val.
3. Help establish the linkages between lidar-based SSH measurements and coincident hydrographic in situ measurements of dynamic height (see Sect. 6.4) for the purposes of science validation.

Assuming the successful validation of the MASS system during the pre-launch period as described above, the system will be flown at the primary ocean Cal/Val site over an intensive three-week period at the beginning of the calibration phase of the mission and again over a two-week period near the end of the calibration phase. The first flight campaign will provide initial data for SWOT calibration, validation, and troubleshooting. The second campaign will enable the validation of any on-board updates made in response to insights gained from the first campaign and will also allow for updated lidar data acquisition strategies based on experience from the first campaign.

While the MASS lidar will be the main SSH validation tool, used over the principal US Cal/Val site during the fast sampling phase, tests are to be conducted with a separate French airborne lidar system for possible use at a second ocean site during the fast sampling phase (e.g., Mediterranean Site). If conclusive, this would enable SSH calibration and validation over more diverse dynamics and surface roughness (wind, wave) conditions.

3 KARIN CALIBRATION PLAN

3.1 Calibration Parameters During Instrument Checkout

During the instrument checkout phase, the JPL Cal/Val and KaRIn System Engineering teams will collaborate in determining instrument parameters required before transitioning into the one-day repeat orbit science phase. By the end of the instrument checkout phase, all parameters resident in the flight hardware and used for on-board processing will be calibrated with sufficient accuracy that data from the Cal/Val and science phases can be reprocessed on the ground at a later date to meet performance requirements with updated, ground-derived calibration values. The parameters to be calibrated and the calibration methodologies are listed below:

3.1.1 Differential Range Delay

Channel to channel image correlation. See section 3.2.1

3.1.2 Common Range Delay

Corner reflector sites, comparison with nadir altimeter, and radiometer. See section 3.2.4

3.1.3 Functional Validation of the Ocean Onboard Processor

During the fast sampling phase, high resolution raw data will be transmitted to the ground for selected ocean regions, together with data processed by the onboard processor for the same regions. These data will be processed with hardware and "golden model" software simulators of the onboard processor to validate its performance. The data will also be compared against averaged data produced by an independent high-resolution interferometric processor as an independent functional validation of the onboard processing approach.

3.2 Calibration Parameters During the One-Day Repeat Phase

3.2.1 Differential Range Delay

This is the simplest parameter to calibrate, as it can be done without the need for external data. The process to estimate the differential range delay is to perform range cross-correlation measurements between images of the ocean and to vary the relative range delay in the images until the cross correlation is maximized. The accuracy for this process depends on the number of scenes used for cross-calibration, and the expected accuracy easily exceeds 1/100 of a range pixel. This technique was demonstrated in the calibration of SRTM (Farr et al., 2007).

3.2.2 Phase Screen

The phase screen can be estimated by comparison to SWOT-independent data or by SWOT self-consistency approaches.

Considering SWOT-independent sources of truth data sufficient for phase screen calibration, MASS under-flights are the primary approach for estimating or validating the phase screen. A 100 km by 140 km swath is built at the time of a SWOT overflight, and the resulting topography mosaic is interpolated to the SWOT along-track/cross-track swath coordinate system. This area may be subsampled by the aircraft if needed due to coverage limitations, but a large area is required in order to beat down SWOT noise. The additional error due to subsampling the truth must be incorporated into the error analysis and flight pattern design. The resulting topography is subtracted from the

SWOT topography, and, for each along-track position, a constant bias and linear trend are removed (since these are considered part of the static phase/roll biases of Sect. 3.2.3 by convention). The estimated biases and trends are used, together with other data, as explained below, to estimate the static range and roll biases. The residual topographic variations for each swath can be related to phase variations by means of the equation

$$\delta\phi \approx \frac{x\delta h}{2kB}$$

where $\delta\varphi$ is the residual phase, δh is the residual height, k is the electromagnetic wavenumber, B is the baseline length, and x is the cross-track distance. Notice that this equation does not depend on the along-track position and one can average in the along-track direction to reduce the random height noise from both KaRIn and MASS. The subsequent profile is aggregated over multiple under-flights and the final average is fit with a Chebyshev polynomial of relatively low order, to protect against over-fitting. The resulting two functions (one per swath) constitute the interferometric phase screen correction, which is subsequently applied to both low-resolution ocean data and high-resolution land data.

The minimum number of flights required to meet the phase screen requirement is dominated by the noise in the KaRIn measurement itself. An estimate has been derived (Rodríguez and Chen, 2015) given the need to meet the phase screen hydrology requirement, which leads to the requirement for phase screen residuals to be less than 1.2 cm, and the KaRIn performance estimated by system engineering (D. Esteban-Fernandez, personal communication). The results are presented in Figure 7, which shows that a relatively small number of sorties will be required in order to provide appropriate calibration.

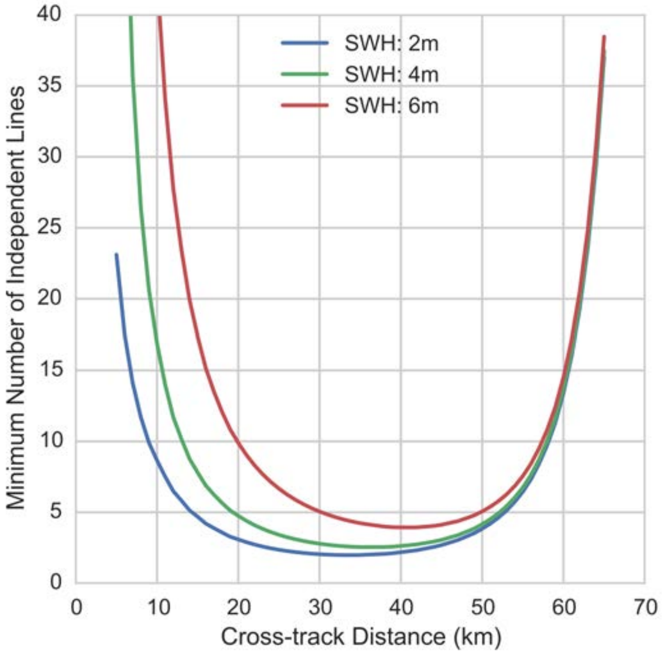


Figure 7. Minimum number of independent lines required to estimate or validate independently the phase screen correction.

An alternate approach to estimating the phase screen and static phase/roll biases is to use KaRIn and altimeter cross-overs that occur within periods of less than one day, which will always be the case during the fast sampling phase. In that case, the variability in the cross-over is primarily due to the uncalibrated phase screen, with a low-wavelength random contribution due to tropospheric delays and potentially low-wavelength EM biases or internal tides effects. Rodríguez and Chen (2015) have shown that it is possible to estimate the phase screen to much greater accuracy than that required by the hydrology phase screen requirement by non-parametric inversion of phase screen from the one-day cross-over differences. The accuracy of the inversion will vary with the significant wave height and the spatial variability of the phase screen itself. As a worst-case example, Figure 8. shows the estimated phase screen errors for a significant wave height of 6 m and high frequency phase screen variations based on retrieving the phase screen using a single cross-over. It is clear that this method will be much more accurate than the airborne instrument phase screen estimates, although it is not independent of the KaRIn data itself. The nominal plan will be to use a number of cross-overs for phase screen calibration and validation will be done using a mixture of airborne flights (independent validation) or cross-over estimates not used to derive the calibration parameters.

The phase screen can also be estimated from SWOT data only along with ocean model estimates (Dibarboure, 2016). The disadvantage of SWOT-only estimation approaches for the phase screen is that many types of errors can masquerade as phase screen effects but would result in unstable phase screen estimates. This is because of the many degrees of freedom in the phase screen, which allow for overfitting of other error contributions that may vary in time or with dependencies different than the phase screen itself. The use of independent data has historically been helpful in diagnosing and resolving such issues when calibrating interferometric SAR systems.

At the end of the phase screen calibration experiments, one will also have an estimate of the static phase/roll angle bias for each swath. This estimate will be averaged to that obtained from the cross-over calibration described below.

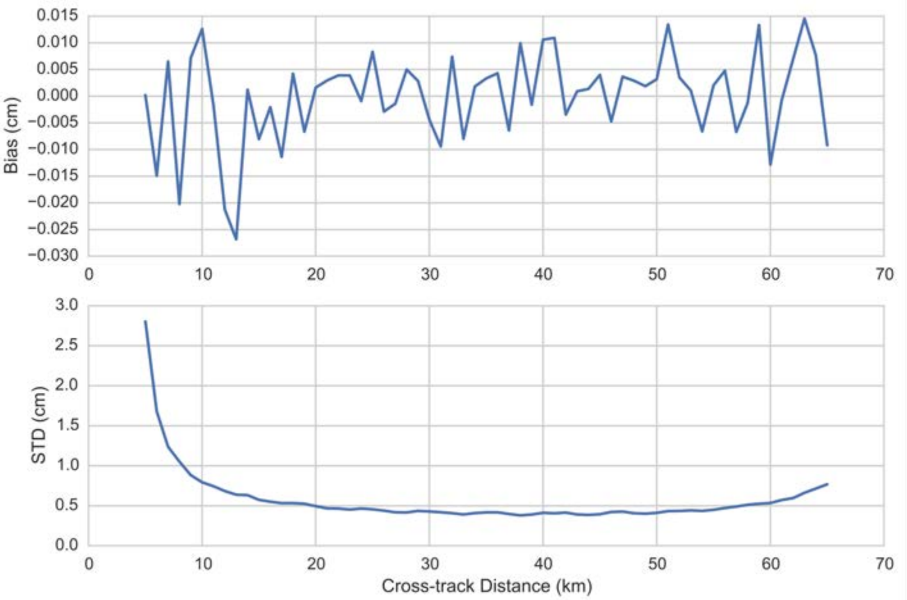


Figure 8. Residual estimated biases and standard deviations for phase screen retrieval based on a Monte Carlo simulation of phase screen retrieval for 6m SWH assuming only 1 cross-over is used.

3.2.3 Cross-Over Calibration for Static Phase/Roll Biases

While the MASS under-flights will produce estimates of the static phase/roll bias along with the phase screen, the accuracy of the estimates will be limited by having to average over dynamic roll errors that will be present simultaneously. Additional information regarding this bias can be obtained and incorporated by assuming that, after correcting for tides and high frequency phenomenon (pressure and winds) but also sea state bias, the ocean surface does not move significantly between ascending and descending passes at orbit cross-overs so that the interferometric phase/roll errors at the cross-over diamonds can be estimated from the KaRIN height differences (Fu and Rodriguez, 2004). (Note that to perform the phase/roll bias estimates, it is not necessary to use the nadir altimeter data.)

Since the KaRIN phase bias will be common between ascending and descending passes, it will cancel when calculating the cross-over differences. However, there will some differences in the elevation measurements due to changes in the wet troposphere correction and the sea surface height. The tropospheric errors are partially mitigated by application of the radiometer correction, although some random cross-track variations may remain.

The contamination due to the evolution of the sea surface height is partially mitigated by using cross-overs during the 1-day fast sampling phase, when the time difference between ascending and descending passes will be less than one day. To assess the impact of ocean motion, we use the high resolution ECCO2 ocean model (see Menemenlis et al., 2008 for a review) of the North Atlantic to simulate the accuracy of phase/roll error retrieval (see Figure 9).

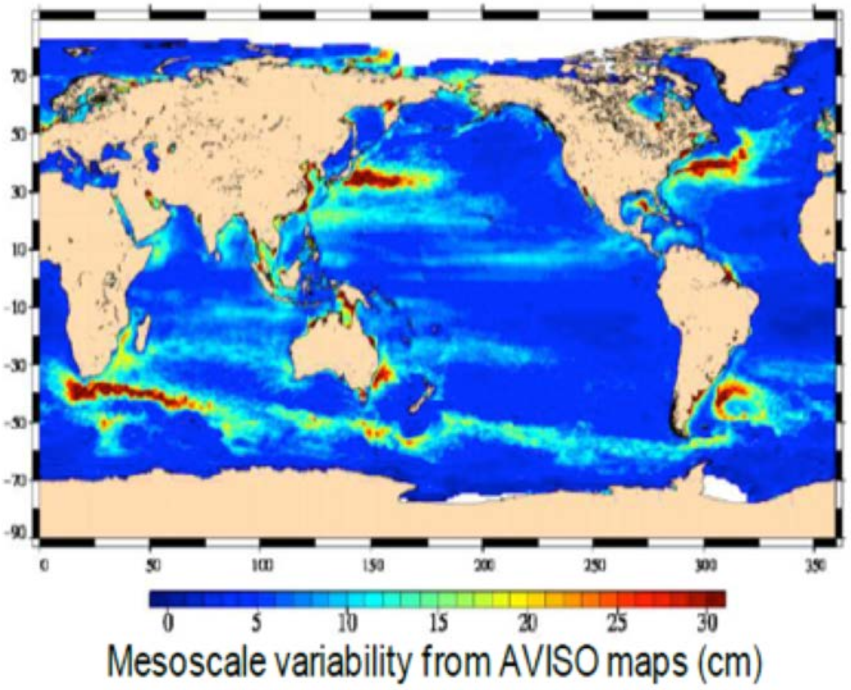


Figure 9. Mesoscale variability from AVISO maps.

To obtain bounds for the problem of the effects of ocean motion, the retrieval accuracy is estimated including instrument errors, but no surface motion, and assuming that the nominal SWOT 21-day orbit determines the cross-over revisit time. The results of this simulation for the residual height error after phase/roll error corrections are presented in Figure 10. Clearly, the biases can be retrieved with more than sufficient accuracy in the absence of ocean motion. Given the typical temporal correlation time of the ocean surface mesoscale circulation, which is on the order of 20 days (see, e.g., Le Traon et al., 1998), we expect the results from the fast sampling phase to closely match these results, especially if one stays away from areas of significant mesoscale activity.

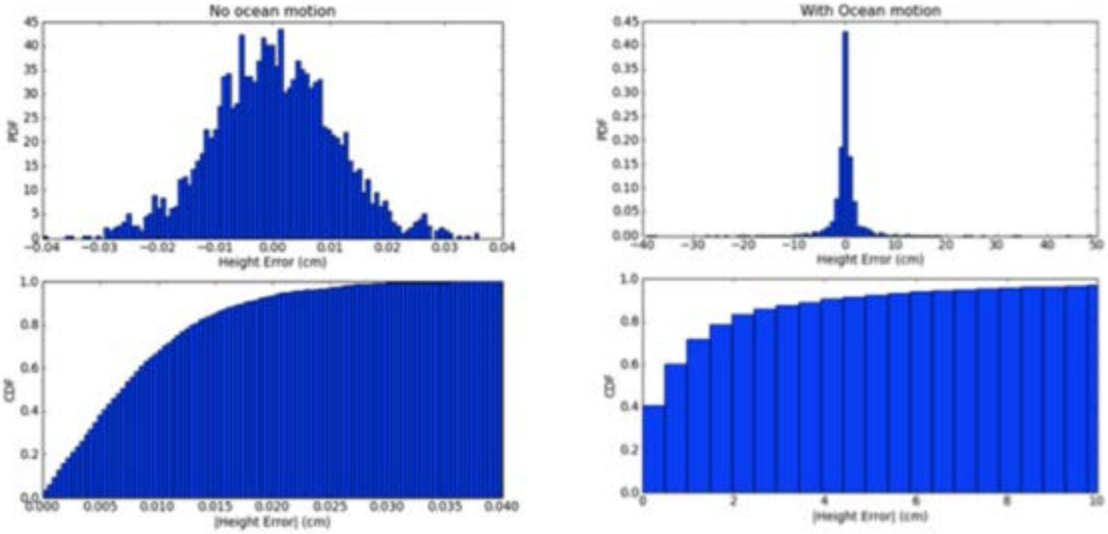


Figure 10. Probability density function (upper panels) and cumulative distribution function (lower panels) of height errors after correcting for unknown phase/roll errors in the case where there is ocean motion (left column) and in the case when the nominal orbit cross-over set is used (right column). In the case when no motion is present, almost all errors are below 0.03 cm. When significant ocean motion is present, 68% of the errors are <1.5 cm, 80% of the errors are <2.0 cm, and 90% of the errors are <5.0cm.

The cross over estimates for the nominal mission will be optimally merged with the data from the onboard gyro, using the known correlations and variances for gyro, phase, and sea surface height. These estimates will be used during the nominal mission to further reduce the dynamic variability of the roll/phase biases. As an example of the benefits of using this cross-over information, or dynamic ocean calibration, for ***continuous dynamic calibration***, Figure 11 presents the results of optimal merging ocean and gyro information to improve the roll correction over land significantly over the result that could be obtained using the gyro information alone. Significantly better results will be obtained over the ocean due to the density of cross-over points and the short along-track temporal separation between them (although meeting the mission error budget does not rely on this process).

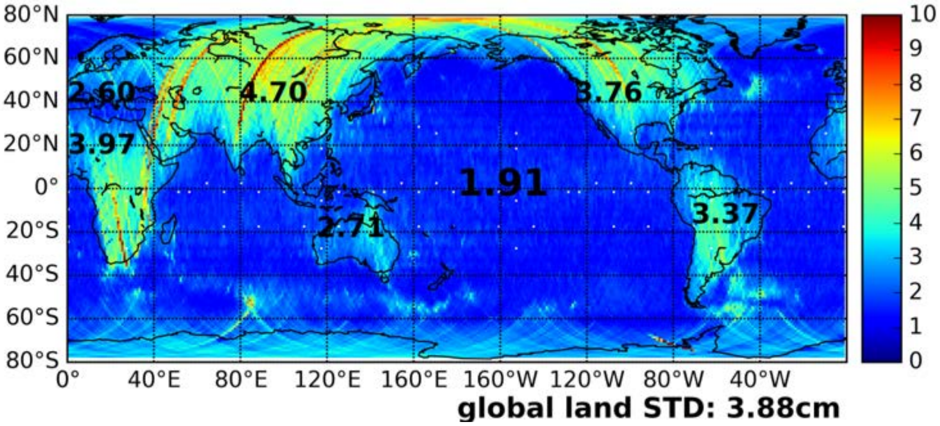


Figure 11. Expected residual phase/roll errors over land in centimeters for the science orbit.

3.2.4 Static Range Biases

The problem of absolute range calibration is one of the most challenging for both conventional altimeters and radar interferometers. In fact, for all altimeter systems to date, *ad hoc* constant bias corrections have been required to ensure consistency for the measured sea surface.

Therefore, for SWOT, rather than requiring that the absolute range be measured precisely, we require that the mean sea surface produced be *consistent* with that produced by the historical Topex-Jason 1-Jason 3 climate data set, which has been cross-calibrated with data collections obtained simultaneously. Both the nadir altimeter and SWOT need to be calibrated to each other and to the reference altimeter data set, including the member of the Jason series operating at the time of the SWOT launch. (Note that if no such satellite exists, the process outlined below will still insure that the SWOT altimeter and KaRIN are at least consistent with each other).

As a first step, we cross-calibrate KaRIN and the nadir altimeter on SWOT. Rather than using the ascending-descending cross-overs, which are contaminated with residual errors due to temporal differences in wet troposphere and sea surface dynamics, we use along track data collected at the same time to obtain this calibration. The KaRIN sea surface height (SSH) field is optimally interpolated across the 20 km nadir gap and the resulting elevations are compared to the altimeter height estimates. Since the ocean SSH spectrum decays quickly with decreasing spatial scale, one expects the contribution due to interpolation errors to be zero-mean and significantly smaller than 1 cm, especially over regions of low mesoscale activity. Thus, by averaging the interpolated height difference over the entire fast-sampling phase, one obtains an average range difference that is significantly smaller than that required by the SWOT error budget. This process can be further optimized if the optional KaRIN nadir channel is implemented (by adding a nadir looking receiver to the radiometer antenna), as this would allow direct comparisons of range delay at nadir, without the need for spatial interpolation.

Obtaining consistency with the reference altimeter constellation must rely on cross-over data, which is not collected simultaneously and will be contaminated by wet troposphere and SSH dynamics. However, assuming slow drifts for the range bias for both systems, an appropriate accuracy can obtained by averaging the observed differences over a suitable time (months).

3.2.5 Radiometric Calibration

Radiometric calibration of SWOT will be obtained by comparing radar cross section for SWOT and AirSWOT when coincident measurements are available at the same set of incidence angles. SWOT estimates of reflectivity will also be compared to model estimates based on wind speeds from weather models and buoy data. The radiometric calibration will also be informed by examining corner reflector data, although discrete-target effects may add some uncertainty to the corner reflector reflectivity estimates. Transponders can be considered as an alternative to corner reflectors.

4 NADIR ALTIMETER CALIBRATION PLAN

Requirements on the performance of the SWOT nadir altimeter are very demanding, notably because the drift of long-wavelengths is challenging to validate with a 3-year mission (as opposed to 10+ for Jason-class). Many instrumental features will be checked (functionally) and characterized notably with respect to the ground acceptance test measurements. It concerns mainly: the tracking capabilities, the shapes of point target response (PTR) and the low pass filter (LPF), the values of CNG attenuators. The impacts of the various configurations of the altimeter performance will be evaluated in detail. The high level requirements for the in-flight assessment of the altimeter will be provided by the CNES team in charge of the instrument. In the following sections, the main SWOT nadir altimeter functionalities that will be carefully checked are recalled.

4.1 Tracking modes

The tracking modes are inherited from the Poseidon-3 altimeter of Jason-3:

- **Close loop:** the acquisition mode is median or Diode, and the only tracking mode is median.
- **Open loop:** the acquisition and tracking mode is called Diode/DEM (Digital Elevation Model). Note that it will be possible to evaluate the Diode/DEM mode even when it is not operating on board. The telemetry actually contains simultaneously, the median tracker data and tracker data computed with this mode. This possibility will allow a complete cross comparison of the modes characteristics.

Tracking modes will be validated during the Cal/Val phases. The objectives are to check the operability and the performances of each tracker mode. Typical metrics are data availability, data coverage and global altimetric performances in a classical CalVal measurements quality sense. The tracking modes will be assessed over ocean but also over sea/land transitions and over hydrological, sea-ice and land ice areas.

Before the end of the assessment phase, the project team will have the necessary metrics and comparison studies between these modes to be able to select the “nominal tracker mode”. The validation plan for the Diode/DEM mode is detailed in the following section.

4.1.1 The Diode/DEM tracking mode

This tracking mode has been already implemented on the Poseidon-3 altimeter (on-board Jason-2&3), on SARAL and on the Sentinel3 missions. Moreover, Poseidon-3C will have the capability to switch from the autonomous tracking mode to the Diode/DEM coupled tracking mode automatically depending on the actual position on the orbit. This automatic transition can be activated or deactivated by ground telecommand.

The target’s predicted distance is calculated directly by the altimeter, combining altitude data from DORIS/Diode with the altitude from a pseudo Digital Elevation Model (DEM) recorded in the altimeter's onboard memory. Depending on the quality of this DEM, the positioning accuracy of the return echo in the altimeter's receiving window is of the order of a few meters. The combined use of Diode data and the altitude from the DEM enables the position of the reception window to be controlled directly, which in turn enables any target to be tracked independently of the type of return echo. This mode is therefore very useful when tracking over areas of special interest, such as rivers and lakes and coastal areas.

The onboard DEM is a series of water altitudes with respect to the Diode geoid, sampled at a constant angular step along the satellite path (0.01°) and corrected from the mean atmospheric and ionospheric delays. Since the projection of the radar spot on the ground covers a circular area of about 8 km of radius, the radar signal may be composed of both water and land contributions in coastal or lake/river areas (Figure 12). As the mission objective is the measurement of water surface altitudes, such DEM points are assigned to water points and the corresponding DEM altitudes are recorded as the altitude of the nearest water point (Figure 13). This enables the altimeter to follow the water areas before and after they have been effectively overflown by the satellite.

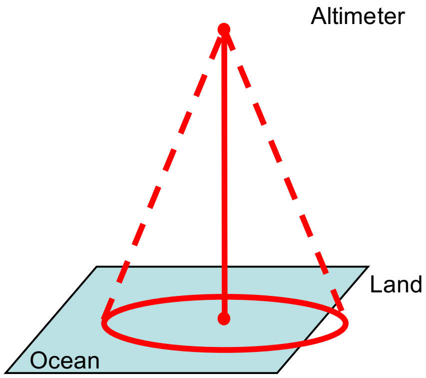


Figure 12. DEM sampling along the orbit path.

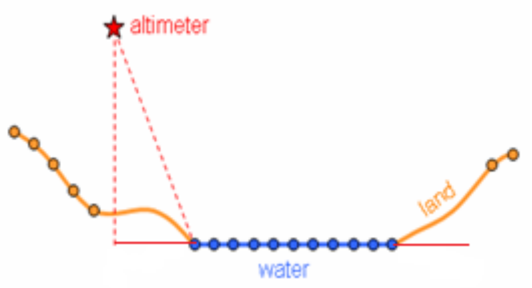


Figure 13. DEM sampling along the orbit path. Extension of areas of interest (water).

Two coding algorithms are used for the onboard DEM storage:

- **Absolute coding:** Successive points of altitude variations within a given threshold (±2 meters over water surfaces) are gathered into segments of same altitude (2 bytes for the altitude of the first point + 2 bytes for the number of points in the segment). The ocean and the inland waters (flat surfaces) are coded this way.
- **Incremental coding:** Successive points with higher altitude variations are coded as follows: Altitude of the first point (2 bytes), then altitude increments (1 byte each).

As the onboard memory is limited, the whole DEM cannot be uploaded. The strategy is to code only the well-known hydrological surfaces, in terms of location and elevation. It will be possible during the mission lifetime to update the DEM by adding other hydrological surfaces of interest. The ocean has also been coded.

4.1.2 The Diode/DEM tracking mode validation

Since the DEM altitudes recorded in the onboard memory are dependent on the satellite orbit, the prerequisite of this plan is the compliance of the actual satellite orbit with the nominal orbit.

Performance assessment indices:

The DEM tracking mode performance will be assessed with two indices giving information on the data availability and the data accuracy:

Data availability will be assessed by comparing the number of measurements acquired using the DEM tracking mode with the number of measurements acquired over the same area using the autonomous tracking mode. A "data availability index" combining these two numbers will be defined in order to give an immediate assessment of the acquisition performance of the DEM tracking mode.

Data accuracy assessment will consist in studying the location of the waveforms in the reception window. Especially, one will check that the waveforms are statistically centered in the reception window and bounded in the authorized extension (±10meters over water surfaces). As geographic information will be simultaneously available with the altitude measurements, it will be possible to identify areas where reception signal do not comply with these requirements.

Performance assessment targets

As the altimeter cannot run simultaneously two tracking modes, data will be compared for different acquisition cycles (e.g. a cycle in classical tracking loop and a cycle in DEM tracking mode). However, it has to be noticed that when the altimeter operates in closed-loop tracking mode, the tracking command that would be applied in Diode/DEM mode is available in the product. As a consequence, the two tracking commands can be compared at the same time and the centering of the waveform can be assessed.

Furthermore, in order to make validation results more representative and accurate, it is proposed to perform the validation study by considering four different region types:

- Over **deep-sea areas**, it should be proved that the DEM tracking mode provides at least as many measurement as the closed-loop tracking mode and that these measurements are at least as accurate as the measurements acquired with the autonomous open-tracking loop.
- Since the onboard DEM does not take into account temporal effects such as tides and variations in path-delay corrections, an important validation point is the assessment of the decrease of the tracking performance in **coastal areas**. But one skill of the DEM tracking mode is that the reception window is always close to the measured surface whereas the autonomous tracking mode is usually unable to follow sea surfaces at distances less than about 5-10 km offshore. Over coastal areas the same "data availability" indices as those defined over deep-sea surfaces will be considered. Two cases will have to be addressed:
    - Areas of low tidal effects: These areas will be of interest to assess the increase of data acquired with the DEM tracking mode with respect to the number of measurements acquired in closed-loop tracking mode. These regions will also be used to check that the slant measurement of the sea surfaces, as described in "§The Diode/DEM tracking mode", is efficient during sea-land and land-sea transitions.
    - Areas of high tidal effects: Over these areas, there might be less data than over areas where low tidal effects occur. However, since the DEM tracking mode is designed to center the backscattered signal in the reception window, some measurements will be exploitable if they are not too far from the tide-free altitudes recorded in the DEM. Therefore, it should be possible to compute the 'data availability' index and then to assess the performance of the DEM tracking mode.

- The DEM is intended to enable altimetry measurements over **rivers and lakes**. The validation process will be conducted in two steps and by considering each lake and each river individually:
    - Data availability: The index defined for the validation over ocean areas will be used to assess the improvement of data acquisition in the DEM tracking mode. Furthermore, the DEM tracking mode for slant measurements will have to be assessed in land/water transitions.
    - Data accuracy: coherence of measurements acquired in the two tracking modes by computing the bias and the scattering of the differences of altitudes will be checked. In case of evidence of an existing bias in the measurement for one or several lakes/rivers (e.g. Wave form not centered in the reception window), one will propose to correct the corresponding altitudes recorded in the DEM and to proceed to an upload.

4.2 Internal Calibrations

The altimeter provides measurements between the overflown surface and the physical point where the deramp process is applied inside the instrument. The altimeter range is then computed between the antenna and the ocean surface. The measured range has consequently to be corrected for the internal group delay that is computed precisely on ground before launch. Of particular importance are the group delays introduced by the duplexer and the antenna. The measured delays will be treated as corrections in the ground processing. However, a part of the group delay can be computed (and monitored) thanks to the point target response (PTR) measurement. It will thus be possible to continuously update this contribution after launch.

Two internal calibration modes are implemented in the Poseidon-3C instrument (as for Poseidon-3B):

- The first mode (CAL1) gives the measurement of the instrument point target response by feeding the signal from the emission channel back to the receiver channel.
- The second mode (CAL2) gives the transfer function of the altimeter receiving chain.

These calibration modes (with various parameters configurations) are fully characterized before launch during the ground acceptance test. During the assessment phase, a complete set of scenario must be played in order to functionally validate a large set of possible configurations of the calibration parameters. The objective is to guarantee the good operation of the instrument and to characterize the various features of the calibration responses. Then, and for the whole life of the mission, the two modes of calibration (in the same configurations) will be activated several times a day by telecommands (3 times for OSTM/Jason-2, depending on the calibration stability) with a double objective:

- ✓ The first objective is to continuously characterize the shapes and positions of the Point Target Response and Low Pass Filters in order to daily introduce updated corrections in the altimeter processing chains that generate the level 2 products. The main corrections using calibration results are the following:
    - correction of the waveforms by the low pass filter before being retracked,
    - computation of the total power of the PTR in order to correct the sigma0 estimation,
    - computation of the difference of internal paths between the emission and reference channels in order to correct the range estimation.
- ✓ The second objective is to ensure an unceasing monitoring of the instrument, in order to monitor the electronics aging and to check the good health of the equipment.

A comparison between measurements before and after launch will be performed to quantify possible evolutions due to the launch.

CNG (Numerical Gain Command)

In the altimeter receiving chain, two numerical gain commands (CNG) are present in order to adjust the amplitude of the echo return to a nominal value. In the ground processing, the sigma naught coefficient is determined thanks to the estimated power computed by the retracking algorithm and the numerical gain commands that were used on board. It is then necessary to precisely know the real attenuation value that has been applied. The CNG values have been measured during the ground acceptance test. However, they are open to drift with time due to the aging of the components. It is thus necessary to regularly calibrate the CNG thanks to a method based on the analysis of a set of PTR measurements. This calibration will have to be done during the assessment phase and repeated regularly (every 3 or 6 months, depending on the calibration stability) during the whole life of the mission.

Simulator of performances

Developed first in the frame of the SSALT Poseidon-1 altimeter onboard TOPEX, a simulator of performances has been consolidated and updated with characteristics and new functionalities of Poseidon-2 and Poseidon-3 altimeters (new tracking modes, updated instrumental characteristics, point target response and low pass filter, CNG tables, and various hardware characteristics). This simulator (validated notably by the good agreement between the ground tests performance of Poseidon-2 instrument and simulation results) will play again an important role during the Poseidon-3C assessment phase. Performances computed with the pre-launch Poseidon-3C acceptance test measurements will serve as references for the in-flight assessment phase.
This simulator of performances will also be used to generate the Look Up Tables (LUT) corrections (for range, significant wave-height and sigma naught coefficient), before and after launch. Those LUT are required to account for the potential ground processing approximations (for example the MLE4 can be implemented with an approximation of the PTR based on a unique Gaussian function).

Altimeter measurements

Measured altimeter parameters will be evaluated after launch. First of all, the science parameters will be studied: e.g., range, SWH, backscatter coefficient, mispointing angle, and waveforms. These studies will include noise-level estimates using Fourier Transform analysis as well as computation of along-track statistics (mean and standard deviation) over the ocean and other surfaces. Histograms and dispersion diagrams will also be computed for these parameters. The results will be compared to equivalent results from previous Poseidon-3 altimeters.

5 WATER VAPOR RADIOMETER CALIBRATION PLAN

The SWOT microwave radiometer provides an estimate of the wet tropospheric path delay in the center of each KaRin swath. The radiometer system consists of two independent three-frequency radiometers feeding a shared 1-m reflector. The radiometer design is based on the Jason Advanced Microwave Radiometer.

The radiometer gain and offset are calibrated at a plane internal to the radiometer using a noise source and Dicke switch to a reference load. The gain and offset are referenced to the instrument input by correcting for the loss and self-emission in the RF front-end components outside of the calibration loop. The internal references and the front-end path loss are calibrated pre-launch and tuned on-orbit.

5.1 Brightness Temperature Calibration

The AMR brightness temperatures (TBs) will be calibrated to on-Earth brightness temperature references. The on-Earth references are a so-called vicarious cold reference (Ruf, 2000), which is a statistical lower bound on ocean surface brightness temperature and pseudo-blackbody regions in the Amazon rainforest (Brown and Ruf, 2005). These references have been used for the calibration of all previous NASA altimeter radiometers.

During the initial Cal/Val period, dependencies of the calibration on instrument temperature will be removed by sampling the TB references as a function of the AMR thermistor measurements and reducing the slope to zero. After that, an Advanced Radiometer Calibration System (ARCS) will be used on a continuous basis during the mission to facilitate the long term calibration. ARCS was originally developed for Jason-2 and Jason-3, and will be developed for Sentinel-6 and SWOT. ARCS uses the comparisons to the on-Earth references to both monitor and correct the long term calibration.

The on-Earth references will be mainly used to set the radiometer absolute TB calibration and to identify and remove any residual instrument temperature dependent errors. To identify and correct for other potential systematic errors that are spatially or temporally correlated, comparisons of the radiometer to modeled TBs and measurements from other radiometer sensors will be used.

Model TBs are generated using numerical weather prediction model fields and a radiative transfer model to simulate what the sensor should be observing. Inter-sensor comparisons are performed by finding co-incident match-ups and deriving AMR equivalent TBs from the other sensors TB observations. Both the model TB and inter-sensor TBs have about a 2-3K uncertainty for an individual match-up. But, this uncertainty is Gaussian distributed and averages down with a large enough sample set. Typically, comparisons over 1 month reduce the uncertainty in the comparison to the 0.1K level. These match-ups are averaged spatially and temporally to identify errors in the antenna pattern correction algorithm, which appear as spatially correlated errors.

5.2 Inter-beam Calibration

Because two independent radiometers are used to derive the path delay slope across the swath, it is essential that they are well inter-calibrated. Statically, the difference between the two radiometer measurements, which are separated by about 80km across-swath, can be represented as a random process with a zero-mean Gaussian distribution. This means that given a large enough sample set, any deviations from zero represent real calibration errors between the sensors. Inter-beam differences will be compared in a number of ways to assess the inter-calibration quality. Monthly maps of the differences will be used to assess geographically correlated errors. Scatterplots of the TBs will be used to assess relative differences in the slope and offset of the calibration. Finally, the daily averaged global mean inter-sensor difference will be used to calibrate relative drifts between the two radiometers.

6 SWOT VALIDATION PLAN

6.1 Introduction

6.1.1 *Overview*

In this chapter, we describe the overall performance validation plan for ocean (Sects. 6.2-6.4) and surface water (Sects. 6.5-6.7) products.

In Section 6.2 we describe how each contributor to the ocean error budget will be validated independently (e.g. to confirm that the measurement system, including instrument, spacecraft, and processing, behaves as expected) and section 6.3 tackles the overall validation of the ocean product, notably in terms of wavelength decomposition (as per the science requirements). Section 6.4 addresses science validation of ocean dynamic heights.

In Section 6.5, we describe how each contributor to the surface water error budget will be validated independently (e.g. to confirm that the measurement system, including instrument, spacecraft, and processing, behaves as expected) and section 6.6 tackles the overall validation of the surface water product. Lastly section 6.7outlines the plan to characterize the river discharge parameters, as per the science requirements.

6.1.2 *Minimum CalVal engagement*

The CalVal activities for the mission will be jointly financed by the NASA and CNES Projects. CNES engages to actively participate in the SWOT CalVal activities detailed in this document, including the global statistical CalVal and participation in certain in-situ CalVal sites, as it has done with all of the past NASA/CNES altimetric missions – Topex/Poseidon, Jason-1, -2, -3 series, etc.

6.2 SWOT Ocean Error Budget Validation

In this section, we describe how each individual component of the SWOT error budget will be validated. The validation of Nadir altimeter data will inherit from the methods used for conventional altimeter missions such as Jason-3. To validate SWOT data globally, three methods will be used:

- Statistical analysis of a single data set (Nadir altimeter, radiometer or KaRIN)
- Differential analysis with overlapping measurements from Nadir, and KaRIN
- Comparison to external assets: remote sensing products, in-situ data, airborne data, or models

6.2.1 *Random height error validation*

The purpose of this section is to validate the random height error that is dominating the error budget at the highest frequencies. This is notably the limiting factor for Sea Surface Height (SSH) observability for wavelengths ranging from 1 to 30 km.

6.2.1.1 *Nadir altimeter random height error validation*

As for the Jason-class missions, the nadir altimeter random noise will be inferred from the plateau observed on power spectral densities (PSD) and/or from the variance of high-pass filtered SSH measurements. Geographical variations and the modulation of random height errors by significant wave height (SWH) will be analyzed with global maps and statistics (e.g. PDF, relationship with

SWH). Lastly the temporal variations (seasonal, inter-annual, drifts) of the random error will be monitored throughout the mission's lifetime.

6.2.1.2 KaRIn random height error validation

To validate the KaRIN random height errors, the same metrics will be used as for the nadir altimeter. The global mean and regional PSD will be analyzed to infer the energy of the random noise plateau, and to derive the random height error, as well as its geographical and temporal variations.

Furthermore, specific cross-track classifications will be carried out to infer the cross-track dependency of the random noise (per Figure 14), as well as it modulation by sea state (e.g. surf-board error). Additional external analyses will be performed using WAM and WaveWatch3 model outputs to quantify the influence of swell amplitude and orientation with respect to the satellite track on the random height error.

By launch, the mean sea surface (MSS) and geoid models are unlikely to resolve 1-km features. Consequently, residual geoid error will be present in SSH anomalies from SWOT. The MSS/geoid error is the same of all SWOT pixels in a given location therefore differential analyses (cross-over, or cycle-to-cycle during the 1-day phase) will be used to gauge the SSH variance cancelled out in the difference and its relationship with MSS/geoid signatures (or MSS/geoid formal error maps). This approach will help separate the systematic high frequency error (geoid) from the random KaRIN error.

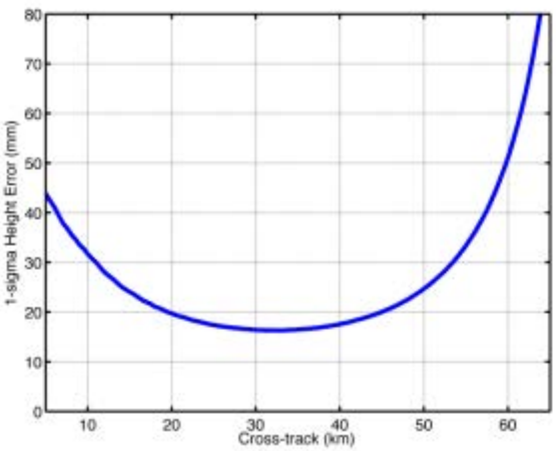


Figure 14. <u>Swath and noise variation.</u> The full width of the satellite swath, from -61 to + 61 km, is measured, with a nominal gap of ±3 km around nadir. However, the data quality is degraded outside of the nominal 10-60-km range. KaRIn random instrument noise varies across the swath, as illustrated in the figure below, with a swath-averaged (10 km to 60 km) height error of 2.4 cm for SWH = 2m for a 1 km^2 pixel. (from JPL D-79084)

In addition to this systematic validation carried out globally, more local analyses will be performed on the so-called 9-beam expert product in order to validate the cross-track variations of the random height error on each beam. These additional analyses will help determine how each beam contributes to the random error of the Level-2 combining SSH content from the 9 beams.

6.2.2 Roll/phase drift validation

The error budget of KaRIN is primarily controlled for wavelengths shorter than 1000 km, as discussed in mission performance and error budget (SWOT_D-79084). In contrast, long term drifts and biases are beyond the ocean science requirements. The longer wavelengths and drifts are however relevant for hydrology. To that extent, the LR processing chain includes an empirical calibration of the KaRIN range drift that is provided as a correction in Low-Resolution (LR) and High-Resolution HR products.

This crossover-based correction will be a direct measurement of the longer wavelengths (>1000km) of roll/phase/baseline errors. It is therefore important to monitor this correction in the long run (e.g. daily or cycle averages, cyclic maps, regional trends throughout the mission lifetime), to try and detect contamination with other phenomena (e.g. verify relationship with in-orbit parameters, sea state or atmospheric conditions) and to analyze extreme and suspicious events.

To gauge the error bar of this correction, it is possible to compare the product corrections with independent drift estimates from other algorithms (e.g. direct and sub-cycle, crossover overlaps with the altimeter constellation, as per Dibarboure and Ubelmann 2013). Similarly, external in-situ sites (like big lakes) will be used to check the cross-track topography profiles, these profiles can be used to infer the long term drift of the roll/phase/baseline systematic errors (see section 6.5.5).

6.2.3 POD Validation

6.2.3.1 Overview

The precise orbit determination (POD) verification activity will rely on a cooperative investigation among project POD teams (at CNES and JPL) and PIs investigators (GSFC, ESOC…) working in this area. CNES has the responsibility for producing the precise orbit estimates that will be included in the science data products. The CNES POD verification effort will take advantage of all available tracking data to produce, on a routine basis, an estimate of the orbit error, as well as an evaluation of the performance of the tracking instruments.

The methods developed to verify the accuracy of TOPEX/Poseidon, Jason-1&2&3 orbits will be extensively used for SWOT. The achievement of the radial accuracy has been confirmed for all nadir missions (refer for example to the OSTST report chapter 6.4 Precise Orbit Determination : http://www.aviso.altimetry.fr/fileadmin/documents/OSTST/2014/OSTST_2014_Meeting_Report.pdf) and the main focus has now moved to the assessment of the long term coherence of the orbits and on the impact of geographically correlated errors on both the global and regional Mean Sea Level estimates: these new objectives are beyond the scope of the SWOT science objectives but they are relevant in the sense that they contribute to the long wavelength SSH error on ocean and on the absolute range error for hydrology.

6.2.3.2 Two types of POD validation

The most critical issues concern the stability of the reference frame used to process DORIS, GPS and SLR tracking measurements, the accuracy and fidelity of the force models that underpin the POD computations and the overall quality of the available tracking data.

The verification activities will be conducted both during the orbit production process (operational verification) and afterwards (expert verification). The goal of the *operational verification* is to ensure that the orbits meet mission accuracy requirements. The operations team performs operational verification during the production of the orbits, and results are summarized in the verification report, which is provided along with the orbit. The project POD team analyzes the results of the verification and authorizes the delivery of the orbit.

The *expert verification* focuses on a more detailed understanding of the nature of the orbit error, and of its impact on the end users. It includes long term monitoring of the orbit quality, especially to enable the early detection of potential drifts. This verification is performed both by the project POD team and by members of the POD Working Group of the Ocean Topography Science Team. This verification is conducted year round, and without a formal time constraint between the production of an orbit and its expert verification. The project POD team expert verification starts during the orbit production process. The members of the POD Working Team conduct their verification efforts once the orbits are officially available.

6.2.3.3 Typical POD validation metrics

The tools of orbit verification are traditionally divided among internal and external tests. *Internal tests* do not need any data other than those used for orbit production. Their key feature is the fact that they can be performed during the orbit production process itself. On the other hand, they usually lack the ability to identify systematic errors. *External tests* are based on the use of data not included in the orbit determination or on orbits produced by different groups using different software and/or configurations. These tests are therefore dependent on the availability of these data. However, they are very powerful at detecting systematic errors and long-term trends. In addition, external tests performed using altimeter data evaluate the orbit quality in terms, which are relevant to the oceanographic users. The list of existing tests is given in Table 2.

Many ancillary parameters are estimated in the orbit determination process. Some of those represent meaningful physical quantities for which valid ranges are known. Others can be correlated with external information. When collected together, these verifications give a different vision of the inner workings of the orbit determination process. As an example, observing the amplitude of the adjusted empirical forces gives a good indication of errors in the modeling of the satellite surface forces. The experience gained with other missions will eventually allow identification and correction of these problems earlier and more efficiently. The parameters that should be monitored are given in Table 3.

Table 2. Precise Orbit Determination Verification Tests

Test	Description	Notes
Data residuals analysis	Analysis of the statistical distribution of the residuals	
Data residuals interpretation	Decomposition of the residuals into time and range biases and analysis of the fluctuations and trends in these biases	The meaning of this test is limited because a cut-off criteria is applied to these biases during data editing
SLR Residuals	SLR Residuals cumulated rms values for measurements performed above current elevation	Allows to observe the relative contributions of transverse orbit errors
High elevation SLR residuals	Selected high elevation laser tracking passes provide an accurate measure of the spacecraft range when it is close to the zenith and thus is a good estimate of the spacecraft altitude	
Single data orbit cross-comparison	DORIS and GPS are used independently to produce Jason orbits, which are then compared together to evaluate systematic errors. SLR residuals are computed for both of these orbits to evaluate the consistency of the 3 data types.	Systematic biases between data types due to incoherent reference systems might overwhelm these tests
Overlaps	Orbits computed for the same time period using different data sets are compared. This test can be used in different ways - overlap between successive orbits (comparison over the few hours in common) - overlap between a 7-day arc and a shorter arc (in this case all the data of the short arc is common to both orbits) - - etc.	These tests provide a good evaluation of the orbit quality Overlaps with reduced dynamics orbits which contain data in common do not provide any information because the orbit very closely follows the data
Altimeter data cross-over residuals	Residuals of the altimeter measurements at cross-over points are computed	The residual signal due to tide model errors and ocean variability is so high that this test does not provide a good estimate of orbit error. However, it is useful to evaluate the relative quality of different orbits.
Comparison between orbits	Orbits computed by different groups using different configuration and/or different software are compared; when long series are available, the main focus is put on geographically correlated radial differences and on the North/South shift between different solutions; special care is taken in observing the stability of these characteristic signatures over time	The usual contributors to the POD expert verification activities are NASA GSFC, JPL and CNES

Table 3. Precise Orbit Determination Ancillary Parameters and Associated Tests

Parameter	Function	Test
Dynamical parameters		
Drag coefficient	Correct errors in the atmosphere density model	Should correlate with solar activity variations
Solar radiation pressure coefficient	Correct global error in the surface force model	Should be nearly constant
Amplitude of 1/rev terms	Absorb errors in the surface force model at the orbital period	Variation with solar angle indicative of problems with solar radiation pressure model
Amplitude of the stochastic empirical force	Absorbs residual dynamical model errors	Level should remain at the 10^{-9} m/s^2 level
DORIS parameters		
Frequency bias per pass	Absorbs frequency offset of beacons	Long term evolution should be compatible with USO quality clock
Troposphere bias per pass	Empirical value of the zenith wet troposphere delay	
On-board USO frequency	Measures frequency of the on-board oscillator	Long term evolution should be relatively smooth
SLR parameters		
Range bias per pass Time bias per pass	Absorbs station calibration errors	Should be relatively constant per station and should correlate well with data obtained with other satellites
GPS parameters		
Clock offset	Offset of the station and satellite clocks	Should behave in a reasonable clock fashion. Should correlate well with the IGS values

6.2.4 Wet-tropo delay validation

The ocean wet troposphere correction is generated using the two-beam radiometer and interpolating the measured path delay throughout the entire swath. The validation of the wet troposphere correction uses a two-step approach: 1.) validation of the wet troposphere path delay from each beam and 2.) validation of the wet-troposphere in the KaRIN swath.

The former uses metrics inherited from the global validation of Jason-class (e.g. Advanced Microwave Radiometer or AMR) radiometers: maps and time series of SSH and crossover variance reduction with respect to a model-based correction, long term monitoring of drifts and offsets. These metrics will be used separately on each radiometer. The comparison between both beams will be performed to rule out anomalies, jumps and drifts that would be specific to a given beam.

The second step is to validate the interpolation mechanism that yields a wet troposphere correction in all pixels of the KaRIN swath. The validation will use similar metrics (e.g. difference between the radiometer-based correction and global model such as ECMWF or NCEP) but applied in bins of cross-track distance: the influence of the interpolation will be measured as bias or varying random error (variance increase) as function of the cross-track distance.

Additional optional validations will be considered during the 1-day phase: co-location of the 2D wet-troposphere correction used on KaRIN product with AMSU-like radiometer imagery. The goal is primarily to validate the cross-track interpolation mechanism and the residual errors illustrated in Figure 15(e.g. non linear effects that are actually measured by radiometer imagery).

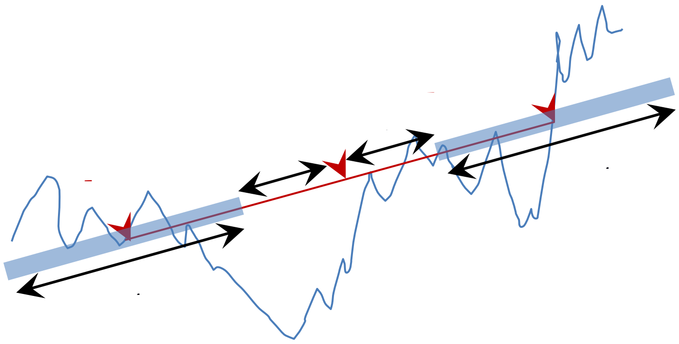


Figure 15. Principle of linear regression between left and right hand radiometer

6.2.5 Other propagation delay validation

6.2.5.1 Ionosphere Validation

<u>Nadir ionosphere correction</u>

The validation of the altimeter correction (based on the Ku/C dual frequency measurement) is herited from Jason-class validation with maps and time series of SSH and crossover bias and variance reduction.

SWOT's orbit is not sun-synchronous and the ionosphere path delay will be modulated by the so called beta-prime angle of the orbit plane. To that extent additional statistics will be computed as a function of solar time in order to quantify and validate that the correction behaves consistently with climatology from the TOPEX/Jason series as well as external measurement from Sentinel-3 and Jason-CS altimeters.

<u>Off-nadir ionosphere correction</u>

The off-nadir correction is based on JPL GIM maps, a very smooth GPS-based model. Although the cross-track variations are generally weak over SWOT's 120-km swath, one can anticipate rare occurrences of ionosphere scintillations events, especially when SWOT's solar time goes through late hours of the day (10PM).

A comparison with local GPS receiver measurements will be considered to quantify their impact on SWOT products, although this comparison is likely difficult to perform due to the very local in-situ nature of the measurement and the possible corruption of coastal or inland measurements from the altimeter.

6.2.5.2 Dry troposphere Validation

The validation of the altimeter correction (based on a global model such as NCEP or ECMWF) is inherited from Jason-class validation with cross-model comparisons with maps and time series of SSH and crossover bias and variance reduction. Additional validations and comparison will be tentatively carried out by the atmospheric model community as part of the science team.

6.2.6 EM Bias and other wave efffect validation

6.2.6.1 Nadir EM Bias Validation

The nadir altimeter SSB algorithm will be inherited from Jason-class algorithms, and the Ka-band correction will be derived from AltiKa (Ka-band nadir altimeter) since Millet et al (2005) have shown that the off-nadir angle measurement should be negligible.

To that extent, their validation is derived from past altimeter mission with maps and time series of SSH and crossover bias and variance reduction, as well as comparisons with other SSB models (e.g. impact of using a non parametric solution or a 4-parameter solution, using WW3 parameters, …). Although difficult to compare due to the influence of SWH on Ka-band sigma0, the SSB correction in Ku/C-band (altimeter) will be analyzed systematically.

6.2.6.2 Off-Nadir EM Bias Validation

Defining the validation of off-nadir EM bias in KaRIN images is challenging considering the lack of maturity of simulations and SSB algorithm definition. The validation of the geometric bias will use metrics derived from nadir altimetry (see above) as well as spectral analyses to infer the influence of the EM bias correction on all scales.

For global ocean, the validation will be based on the comparison between 3 EMB Solutions based on:

- an analytical model, available from the beginning of the mission and fed with SWOT derived products (SWH, Wind...) and potentially with other sea-state environmental conditions from auxiliary datasets,
- a parametric table computed from the one day fast sampling phase residuals (see below), 6 months from launch,
- and a parametric table computed from the crossover analysis, after 1 year of mission.

Comparing these solutions will consist in evidencing potential dependencies to additional parameters in order to refine our understanding of the observed bias, e.g., stemming from surface wave velocity and orientation. It will probably deserve the ingestion of ancillary and/or auxiliary datasets such as Wave Watch 3 global model (wave period, spectral components,…), the OBP wave-mitigation products delivered by the on-board processor...) (Tran et al. 2010).

For more local validation, additional methods to evidence dependencies are envisaged, for instance with parameters derived from systematic co-location with SAR imagery (e.g. operational missions such as Sentinel-1 : http://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Sentinel-1). This will infer sea state conditions in the KaRIN image.

One of the advantages of SWOT over traditional altimeter missions for the validation of the EM bias is the one-day fast sampling phase. During that phase, notwithstanding internal tides and other high-frequency phenomena, one of the main differences at the repeat passes or cross-overs (after calibration of the phase screen) will be the sea state dependent EM bias, which will change from day to day, and very little aliasing is expected from the mesoscale SSH signal temporal variation. Thus, the fast sampling phase will present a unique opportunity to derive estimates of the angular dependence of the EM bias using repeat pass differences, coupled with estimates of sea state. The cross-overs differences during the fast sampling phase can then be used to validate that the EM bias corrections reduce the cross-over variability, as has been done traditionally.

6.2.7 Tidal correction validation

The tidal correction is measured in SWOT's SSH and it is not a part of the error budget. To that extent its validation is beyond the scope of critical project activities. However, the validation of global barotropic tide models is traditionally carried out in collaboration with the science team (e.g. recent review of global models by Stammer et al, 2014) using SSH and crossover variance reduction, temporal harmonic analyses or space/time 2D spectra, and comparison with in-situ tide gauges.

The case of internal tides is somewhat specific since it is an active research topic. Placeholder algorithms and correction are defined for the ocean product and may evolve in the near future. The internal tide correction will be validated using the above metrics with a focus on wavelengths ranging from 50 to 500 km, and accounting for the regional and directional nature of the variability of internal tides. Project validation will be carried out in close cooperation with the Science team.

Validation of SWOT during the 1-day phase will also leverage the daily revisit and the very slow variations of the local measurement time over 60 to 90 days in order to infer the fraction of the internal tides variance that is phase locked and predictable with static models, and the fraction of the internal tides continuum that must be corrected with dynamic algorithms.

6.2.8 Dynamic atmospheric correction validation

The dynamic atmospheric correction (DAC) is measured in SWOT's SSH and it is not a part of the error budget. To that extent its validation is beyond the scope of critical project activities. However, the validation of global barotropic wind and pressure-forced models is traditionally carried out in collaboration with the science team using SSH and crossover variance reduction, and comparison with simple Inverse Barometer solutions based on global atmospheric models such as ECMWF or NCEP.

6.2.9 Rain flag validation

Concerning flag validation, the SRD stipulates that: "SWOT shall provide flagging of height postings affected by rain/sea ice with 68 % accuracy of the rain/sea ice (More than 68% of contaminated data must be correctly flagged)."
And, even though the flags algorithms are still being developed and not fully defined we can already take advantage of nadir altimetry experience (AltiKa, Jason-3, …) to address the fact that:

- flags are well positioned within 68% = less than 30% of false alarms/non detection
- and resulting SSH is relevant after their application

The metrics of quantification will rely on:

- Geometrical methods based on masks comparisons (Difference of surface statistics, differences of RMS between contours…)
- Statistical methods based on single dimension flag comparisons (histograms, dispersions diagrams…

For each, products, flag can be:

- Intrinsic to the measure: mostly based on surface characteristics sensitivity of the instruments, it is dependant on the instrument and its resolution
- Based on external datasets: colocalised (temporally and geographically) in both Radiometer, Nadir and KaRin products

6.2.9.1 Nadir rain flag validation

The validation of the nadir rain flag will be primarily based on the altimeter (sigma0 drops) and the two radiometer beams (tens of kilometers away from the nadir position). Using a variant of AltiKa-based matching pursuit algorithms from Tournadre (2009), a systematic comparison of the points and segments flagged by each dataset will be performed to validate the behavior of each flag. The validation of SWOT products will also use the systematic comparison with radiometer imagers that are currently used for SARAL/AltiKa.

6.2.9.2 Off-nadir rain flag validation

The KaRIN off-nadir rain flag is based on rapid drops in radar cross-section (energy lost due to rain) that will be visible in the 250-m sigma0 mean and variance. Statistics, maps and temporal series will be used to validate the geographic distribution of rain and the typical size of rain cells. Additional comparison with rain radars and radiometer will be used to validate per-pixel flags, albeit only on co-located images.

The positive influence of the rain flag will be gauged using statistics on the SSH when the flag is applied or not in various regions and seasons.

The 1-day phase will also be leveraged to compare subsequent 1-day images in terms of SSH, radiometer wet-tropo and rain flag. One can anticipate that the atmospheric conditions are more likely to change than the SSH. These analyses will help validate that the rain flag is consistent with spurious SSH pixels or spurious wet-tropo measurements.

6.2.10 Ice flag validation

6.2.10.1 Nadir altimeter ice flag validation

The validation of the nadir ice flag will be primarily based on a combination of the Ku-C-band altimeter and the two radiometer beams (inherited from Jason methods). Moreover, waveforms from the nadir altimeter will be analyzed using supervised or unsupervised classification to identify sea-ice echoes (approach inherited from AltiKa algorithms). The positive influence of the ice flag will be gauged using statistics on the SSH when the flag is applied or not in various regions and seasons.

The validation of the nadir ice flag will also use the systematic comparison with sea ice concentration and contours (e.g. Eumetsat's OSI-SAF) and SAR imagers to get the context near the nadir tracks.

6.2.10.2 KaRIN ice flag validation

The KaRIN off-nadir ice flag is based on rapid increases/drops in radar cross-section (e.g. the GPM Ka-band mission observes on average a +/-10 dB during ocean to ice transitions) that will be visible in the 250-m sigma0 mean and variance. Statistics, maps and temporal series will be used to validate the geographic distribution of sea ice. The positive influence of the ice flag will be gauged using statistics on the SSH when the flag is applied or not in various regions and seasons.

Additional comparison with radar cross-section from SAR imagers and sea ice concentration and contours (e.g. Eumetsat's OSI-SAF) will be used to validate per-pixel flags, albeit only on co-located images in some dedicated areas.

6.2.11 Land flag validation

6.2.11.1 Altimeter land flag validation

Along track pollution of data by land will be flagged both in altimeter and radiometer products. Their validation will consist in: comparing them in terms of coverage and quality of SLA when the flags are applied. These results will be mainly analyzed in the fringe near the coasts given by static field (https://www.soest.hawaii.edu/pwessel/gshhg or Globecover, SRTM, ASTER…) or dynamic after cloud preprocessing (LandSat, S3…).

6.2.11.2 KaRIn land flag validation

A land ocean flag limit will be deduced from KaRIN information (sigma0, phase, coherence and information from the average step). To validate it, a comparison to a high resolution (km) land mask is envisaged.
On the one hand, to validate occurrences of non detection of land pollution in ocean images, we propose to compare the SSH statistics, (jointly with Sigma0 and interferometric information) with both masks (external land mask or Karin flag) in a limited fringe (below 20km from coast and for latitudes below 50° in order to avoid mixed information from ice pollution).
On the other hand, to avoid false alarms, we propose to focus on a set of regions and to map the removed data, superimposed to the external land mask. These areas will be chosen for various shore types (rocky steep coasts, large flat beaches…) and this with different tidal behaviors: from negligible to large. Collocation with optical images can also be envisaged for specific areas (LandSat, S3…).

6.3 Ocean Data Product Validation

In addition to the validation of each component of SWOT's error budget (section6.2), the main parameters of the Level-2 ocean products will be validated. Sea surface height (SSH) is addressed in section 6.3.1 using the wavelength decomposition of the science requirements, mostly with using SSH (or SSH anomalies), i.e. a composite of the instrument range and POD, after all path delay and geophysical corrections are applied. To that extent, this section complements the validation of each component described in section.

The validation of significant wave height (SWH) is then discussed in section 6.3.2. The validation of sigma0 measurements is also presented in section 6.3.3, and the validation of wind speed in 6.3.4.

6.3.1 Absolute Range and SSH validation

6.3.1.1 Validation of the Ocean Performance from 15 km to 150 km

Validation of the SWOT ocean absolute height error spectrum at wavelengths shorter than 150 km will be achieved through the methods described in Sect. 2.3.2 (airborne lidar). Science validation of dynamic height is discussed in Sect. 6.4.

Additionally, we can validate some of the smaller mesoscale structures (50-150 km) using 1D SAR nadir altimeter SSH observations collocated in space and time across the SWOT swaths (limited to measurements within a few days). The Jason-CS and Sentinel class altimeters will be flying with a SAR mode, allowing 1D spectral performance down to 30-50 km depending on the geographical region and sea-state conditions. However, since the SAR altimeter tracks will not be exactly aligned with the SWOT track, this method will have some limitations for validating the SWOT along-track spectrum performance.

6.3.1.2 Validation of the Ocean Performance from 150 km to 1000 km

For scales larger than the ocean swath, the along-track spectra from the SWOT altimeter and KaRIN must coincide (within the noise floor capabilities of the altimeter). Therefore, the KaRIN along-track spectrum for these scales will be validated by direct comparison against the simultaneously measured altimeter spectrum. Spectral estimates will be performed for all cross-track pixels in the SWOT swath, to validate the consistency of the KaRIN data and the effect of variations in the wet troposphere, EM bias, and ionospheric corrections that are made based on the nadir altimeter and radiometer measurements. Other altimeter missions flying during this period can also provide additional validation data, for tracks which are collocated in space and within a few days of the SWOT observations, as well as 2D gridded maps which provide a synoptic view of the medium mesoscale.

6.3.1.3 Nadir absolute range and validation of Long-Wavelength Height Errors

For wavelengths longer than 1000 km, the nadir altimeter provides a Jason-class SSH reference for KaRIN. The methods used to validate the long wavelengths of the altimeter are inherited from Jason-class Cal/Val activities, and in particular the comparison with Jason-3, and Jason-CS (alternatively Sentinel-3A and 3B operational altimeters operating at the time of the SWOT launch : http://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Sentinel-3). The Harvest, Corsica, and Bass Strait sites will be considered as well. In addition to the absolute global mean bias, the validation includes the assessment of regional discrepancies (maps of regional bias), as well as investigations on correlations with in-orbit conditions or geophysical parameters (e.g. SSB). These metrics will be completed by comparisons with global in-situ networks such as tide gauges and ARGO (local calibration is addressed in section7.1).

The differences between the nadir altimeter dataset will provide additional metrics to be used for validating the off-nadir KaRIN SSH, as well as some insights on the Ku-band versus Ka-band discrepancies (e.g. ionosphere biases and trends).

Most metrics will be used systematically to derive temporal variations of the Long-Wavelength errors (e.g. seasonal biases, inter-annual variability, or relationship with beta prime angle…).

Ocean measurements will also be used to infer the altimeter regional inland bias using spherical harmonic and/or EOF analysis.

6.3.1.4 Off-nadir absolute range and validation of Long-Wavelength Height Errors and drift

Overview

On ocean, the range error budget of KaRIN is defined for wavelengths shorter than 1000 km, as discussed in the mission performance and error budget (SWOT_D-79084). In contrast, long term drifts and biases are beyond the ocean science requirements for oceanography even if they can be measured on ocean. Long wavelength range errors and drifts are however relevant for the hydrology error budget. To that extent, the KaRIN processing chain includes an empirical calibration of the KaRIN range drift that is provided as a correction in LR and HR products.

One proposed algorithm is to compare the altimeter-based nadir profile to an equivalent 1D profile from KaRIN (e.g. cross-track average in both swaths) and to interpret the difference as a direct measurement of the KaRIN range bias, thus reducing the KaRIN range drift to small values for a corrected topography. It is therefore important to validate this correction and the residual bias (if the operational KaRIN range correction is perfect the residual bias will be zero).

Validation of the operational range calibration

In addition to the absolute global mean bias between KaRIN and the nadir altimeter, the validation includes the assessment of regional discrepancies (maps of regional bias), as well as investigations on systematic errors linked with in-orbit conditions (e.g. separation of ascending and descending passes, relationship thermal conditions) or geophysical parameters (e.g. relationship with SWH or sea state conditions).

These metrics will be completed by comparisons with global in-situ networks (e.g. tide gauges and ARGO) and precise local calibration sites (discussed in section 7.1). They will be used systematically to derive temporal variations of the Long-Wavelength errors (e.g. daily or cycle averages, cyclic maps, regional trends throughout the mission lifetime), to try and detect contamination by other phenomena and to analyze extreme and suspicious events.

Analysis of residual range discrepancies between KaRIN and the nadir altimeter

The study from Dibarboure et Ubelmann (2014) shows that 3 other methods can be used to quantify the long wavelength errors of KaRIN, namely the sub-cycle, collinear and crossover methods. The crossover method is in essence what is done with altimeter range calibration when nadir crossovers are used to determine a long-term drift in the altimeter range. The other two are variants specific to the KaRIN geometry. The combined used of KaRIN and the altimeter will make it possible to separate the platform height bias from POD residual errors that is common to the altimeter and KaRIN, and to isolate the range drift that is specific to KaRIN.

The strength of these methods are not affected by the spatial variability associated with KaRIN/nadir comparisons and less sensitive to directional KaRIN errors since they use a perfect spatial co-location between two KaRIN images or between a KaRIN image and a nadir profile. The downside is that the time difference between co-located datasets will introduce temporal variability. To that extent, it is likely that the range drift will rely on crossover with short time differences. Residual high-frequency variability will be very small with respect to the ocean topography signal: measurements from overlaps between Jason-1 GM / Jason-2 show that the SSH variability for periods shorter than 4 days represents less than 10% of the total SSH variance for wavelengths longer than 300 km (Dibarboure, 2015).

During the first months of mission, the crossover and sub-cycle coverage will be sparse, and the main reference method should be the collinear method (difference between subsequent 1-day cycles).

6.3.2 SWH Validation

6.3.2.1 Nadir altimeter SWH Validation

The nadir altimeter SWH will be validated using heritage from Jason-class missions with statistical analyses (e.g. PDF, spectra), maps of bias and variance, analyses of crossover difference with very short time differences, correlation with in-orbit and geophysical parameters. The SWOT nadir altimeter will also be compared with in-situ buoy data and global models, as well as with operational altimeters that are concurrent with SWOT (e.g. Jason-CS or Sentinel-3). The temporal evolution of these metrics will also be monitored throughout the mission's lifetime to infer possible drifts and jumps associated with onboard events or processor changes.

6.3.2.2 Off-nadir KaRIN SWH Validation

The off-nadir SWH derived from the KaRIN coherence is likely similar to the altimeter SWH profiles, although they are based on a fit that extends through the entire swath. The validation of this product will use the same statistical analyses and external comparison as for the nadir altimeter. Cross-comparisons between the nadir and off-nadir SWH estimates will be performed to rule out the presence of systematic bias, and to quantify the precision of the off-nadir KaRIN SWH.

Moreover, to infer how the natural SWH variability throughout the 120-km swath might affect the off-nadir SWH product, systematic co-locations with SAR images or downstream products (e.g. virtual buoys from Collard et al 2009 in Figure 16) will be used, in particular during the one-day phase where high-latitude crossovers have an extremely short time difference, enhancing the value of comparing two KaRIN measurements with limited external assets. Lastly, the CFOsat mission from CNES and China (https://cfosat.cnes.fr/en/CFOSAT/index.htm) will provide an additional global reference with crossover wave spectra that will be compared with SWOT measurements (e.g. as a function of wavelength or the KaRIN azimuth/range angles).

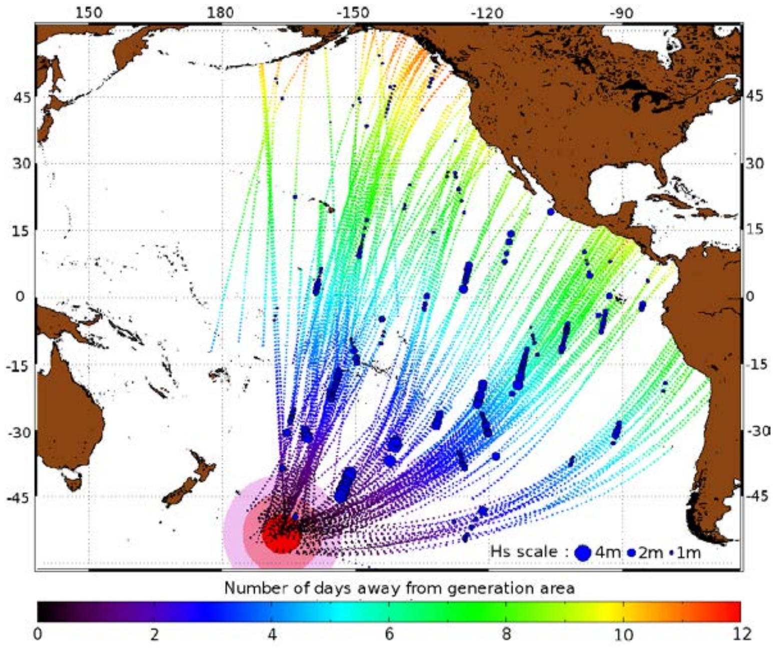


Figure 16. Trajectories of all the swell observations given by the SAR wave mode and associated to the storm of 11 April 2008, South-East of New-Zealand. The generation region is symbolized by a red disk and the color along the trajectories indicates the days of travel since generation. Blue disks are placed at observation locations. Their size indicates the significant swell height at this moment. (Husson et al. 2012)

6.3.3 Ocean σ_0 Validation

6.3.3.1 Nadir σ_0 validation

The nadir altimeter σ_0 will be validated using heritage from Jason-class missions with statistical analyses (e.g. PDF, spectra), maps of bias and variance, correlations with in-orbit and geophysical parameters, analyses of crossover differences with very short time differences,. The SWOT nadir altimeter will also be compared to operational altimeters that are concurrent with SWOT (e.g. Jason-CS or Sentinel-3). The temporal evolution of these metrics will also be monitored throughout the mission's lifetime to infer possible drifts and jumps associated with onboard events or processor changes.

6.3.3.2 KaRIn σ_0 validation

Although there is no science requirement on the performance of the off-nadir KaRIn σ0 performance, the validation of this product will use the same statistical analyses and external comparison as for the nadir altimeter.

To validate the 2D component of the σ_0 images, and to validate the precision and accuracy in KaRIn measurements, co-location with SAR images and Ka-band radars (e.g. GPM/TRMM) will be used. Moreover, internal comparisons between KaRIn products will be performed on a systematic basis. Lastly, the 9-beam expert product will be used in offline studies to validate the high-resolution data used and combined to deliver the Level-2 σ_0 map, and to explain the source of residual variability. These studies will be carried in close cooperation between the project and the science team.

6.3.4 Wind Speed Validation

6.3.4.1 Nadir wind speed validation

The validation the altimeter wind speed product is linked with the validation of the σ_0 (discussed in section 6.3.3) and the transfer function used to derive an absolute wind speed modulus. Therefore, the nadir altimeter σ_0 will be validated using heritage from Jason-class missions and discussed above. Specific comparisons with external data such as global model and scatterometers (e.g. CFOsat operates concurrently a wind scatterometer and a wave scatterometer, thus yielding a very rich reference product for cross-comparisons with SWOT).

6.3.4.2 Off-nadir wind speed validation

Although there is no science requirement on the performance of the off-nadir KaRIN wind performance, the validation of this product will rely on the same approach as for nadir altimetry, and in particular on comparison with scatterometry products and high resolution model outputs to validate the 2D wind products from KaRIN, even though SWOT provides only the wind speed (not direction). The KaRIN σ0 inversion algorithm used to derive wind speed may require model fields as an input, and alternative algorithms and input fields will be generated and compared to the reference product in order to infer the variability and precision of the wind speed inversion process.

An alternate for of validation will be the development of a wind model function from the Global Precipitation Mission (GPM) Ka-band radar, which samples the SWOT incidence angles. This model function can then be used to compare against the one derived from SWOT data.

6.4 Science Validation of Ocean Measurements

A primary objective of satellite altimetry has been to map the ocean dynamic height for the study of ocean circulation. The thrust of SWOT in oceanography is to extend ocean dynamic height to wavelengths shorter than the 2-dimensional resolution of conventional altimetry.

Hydrographic in situ measurements have been a mainstay of oceanography since long before the advent of spaceborne altimetry. These measurements provide direct insight into physical quantities of oceanographic interest, particularly ocean circulation. While geoid and high-frequency effects must be removed from the SWOT measurements of absolute SSH before circulation can be estimated, hydrographic in situ approaches measure dynamic height, which is the quantity of more fundamental science interest that underpins the SWOT oceanographic science objectives. The relationship between absolute SSH and dynamic height have been demonstrated at wavelengths longer than 150 km, but their relationship down to wavelengths as short as 15 km have not yet been fully validated.

Hydrographic in situ approaches rely on conductivity-temperature-depth (CTD) measurements over vertical profiles (ie, as a function of depth) at a given horizontal location in order to integrate vertically the dynamic height. A spatially distributed array of in situ measurements would be needed in order to validate the spectral performance of SWOT using in situ approaches. A 1-D array of fixed moorings with CTD instruments would be the ideal measurement approach. The array spacing would be 7.5 km in order to Nyquist sample the 15 km minimum wavelength required of the SWOT measurement. The array would extend for 150 km (20 moorings) in order to capture wavelengths up to the regime that nadir altimetry alone would offer sufficient validation. Each mooring would ideally include CTD instruments spanning the full depth of the ocean. Each mooring would ideally also include sufficient near-real-time communication that the health and function of the array could be confirmed (or faulty elements could be replaced in a timely manner so as not to jeopardize the tight SWOT Cal/Val timeline), and data could be examined with sufficient time to react to any surprises during the Cal/Val period. Unfortunately, this ideal measurement concept using moorings is not feasible logistically or programmatically. However, an array of stationkeeping autonomous underwater vehicles (AUVs) may be able to reasonably approximate this measurement.

Underwater gliders are AUVs that typically propel themselves by changing their buoyancy, using wings to convert vertical motion into horizontal motion. Some may also be equipped with foldable, propeller-driven thrusters. Gliders typically include satellite-based communications links to operators. With gliders carrying CTD instruments and diving up and down while maintaining approximately fixed locations horizontally, data integrated over the glider profiles can give estimates of dynamic height for validation of SWOT science and spectral requirements. It is not possible to sample the full depth of the ocean with gliders at the candidate Cal/Val sites, but simulations suggest that sampling the upper 500 m of the ocean captures most of the ocean dynamics such that the measurements offer comparable spectral performance to the SWOT baseline requirements, assuming that the SWOT measurements are corrected for the differences between absolute SSH and dynamic height (the SWOT requirements on SSH error spectra have been chosen to be considerably smaller than the expected spectral levels of SSH signals).

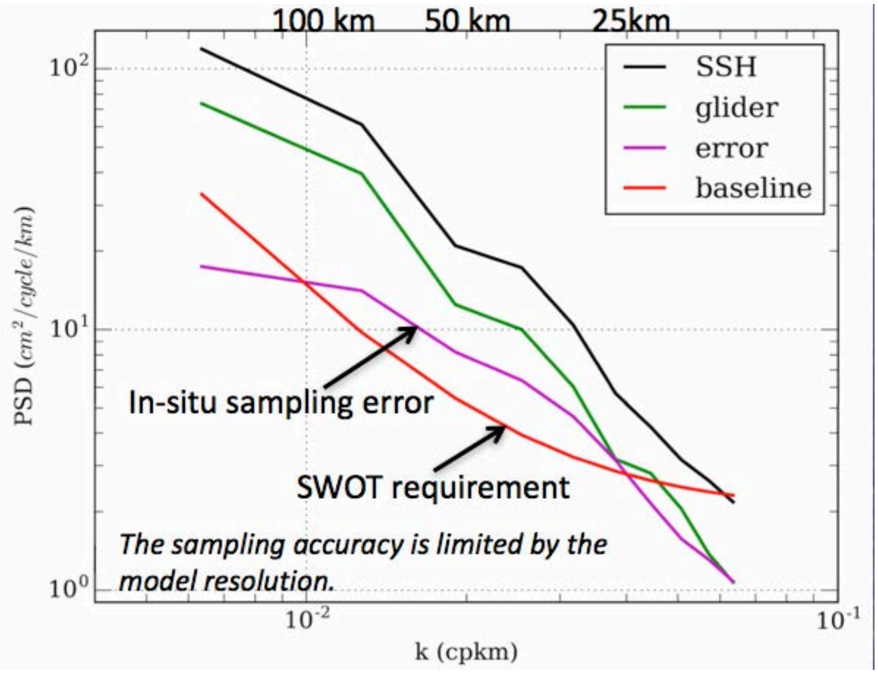


Figure 17. Simulation results considering an array of 20 stationkeeping gliders spaced at 7.5 km apart sampling the upper 500 m of the ocean (see Wang et al., 2017).

In order to mitigate risks associated with the glider concept, an experiment was conducted in summer 2017, comparing real glider performance to a mooring in Monterey Bay. The experiment results show good agreement between the mooring and glider measurements of dynamic height. The results also showed that the gliders tested were able to adequately maintain their horizontal positions and that sampling only the upper ocean rather than the full depth captures variations in dynamic height over time. However, the ocean currents and dynamics at the location of this experiment are not necessarily representative of the primary Cal/Val site.

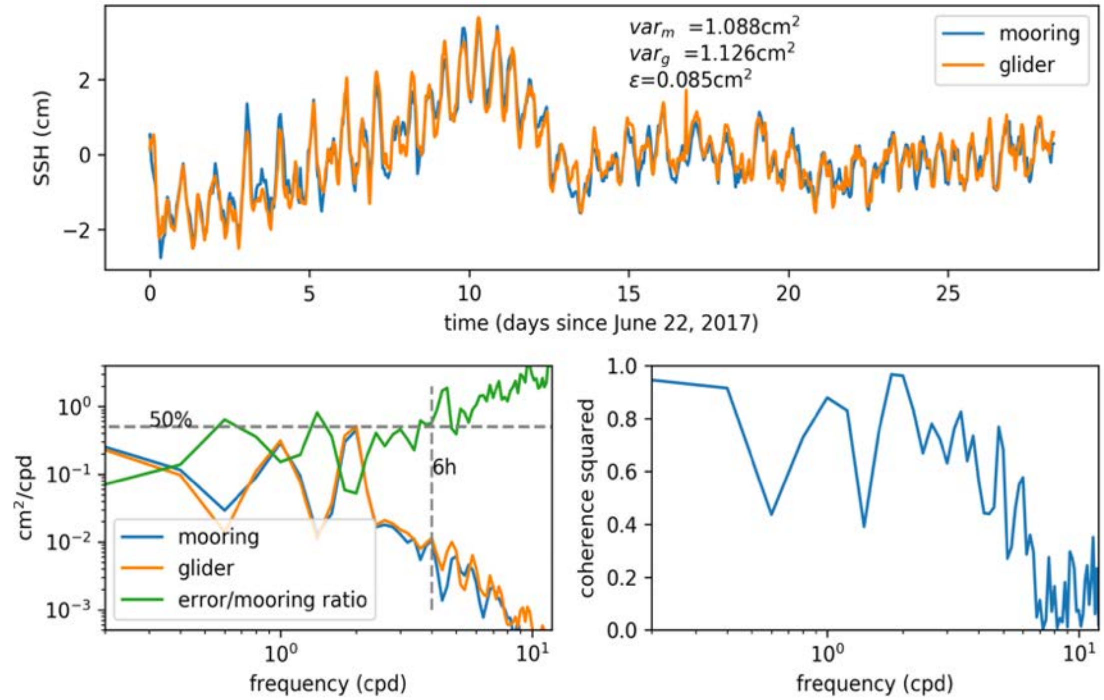


Figure 18. Comparison of a stationkeeping glider to a fixed mooring in Monterey Bay from an experiment in June 2017.

The following uncertainties therefore remain in the ability of a glider array to meet SWOT Cal/Val needs:

1. There is a risk that the gliders may not be able to stay on station in the presence of the currents at the primary (California) SWOT Cal/Val site. Note that analysis suggests that the gliders would not be able to maintain station at the backup (Gulf Stream) Cal/Val site, at which the currents are even stronger. Analysis suggests that the stationkeeping ability at the California site is marginal. Hybrid gliders, which can use their thrusters at the expense of battery power (and hence operating duration), should have sufficient control authority for stationkeeping (via analysis). However, assuming the use of thrusters for SWOT Cal/Val implies that (1) only hybrid gliders can be baselined, which could increase costs and logistic difficulty in securing the use of such gliders; and (2) additional cost, especially in ship time, will be involved to replace the glider batteries during the course of the calibration phase. Constant use of thrusters shortens the operational duration of the gliders from an estimated four months to two months, so covering the 90 day calibration phase of the mission may require an additional ship campaign to replace the batteries of the glider array if the thrusters are needed.
2. There is a risk that sampling only the upper 500 m is not sufficiently representative of full-depth sampling at the primary (California) SWOT Cal/Val site. Note that the depth at the Cal/Val site is approximately 4000 m, while the depth at the site of the Monterey experiment is approximately 1000 m. Increasing the dive depth of the glider profiles would allow deeper sampling (up to the maximum depth of the glider, which varies by glider model), but since each dive would require more time, the temporal resolution of the measurements would degrade, thereby introducing additional error. Temporal resolution could be regained by operating pairs of gliders at each array location, with each glider executing a dive profile that is phased 180 degrees apart from the other. The use of two gliders per array location would

double the total number of gliders, however, thereby increasing the cost and operational complexity of the experiment.

In order to address the risks above, a pre-launch experiment at the California Cal/Val site is being planned that would involve the deployment of one fixed mooring and the concurrent operation of two gliders. These gliders would be Slocum hybrid gliders with thrusters. The desired outcome of the experiment is that (1) the gliders are able to maintain station with no or minimal use of thrusters; (2) the dynamic height measurements of the gliders and the mooring agree, demonstrating that sampling only the upper 500 m of the ocean is sufficient to achieve a level of accuracy appropriate for the science validation objectives.

Assuming that the pre-launch experiment achieves the desired outcome above, there is a proposal for the post-launch science validation to comprise an array of 20 stationkeeping gliders spaced 7.5 km apart covering a 150 km line at the California crossover site. Each glider would sample the upper 500 m of the ocean for the 90 day duration of the SWOT calibration phase. Additionally, one fixed mooring sampling the full ocean depth may be deployed to help cross-calibrate the gliders. GPS instruments are not part of the baseline in situ proposal but could be included as a contribution and/or included if warranted based on other GPS investigations that will be occurring in the pre-launch timeframe.

Note that underwater CTD (UCTD) measurements on a moving ship have been evaluated for SWOT Cal/Val, but due to the slow speed of the ship compared to the very fast overflight time of the spacecraft, this approach cannot adequately capture the temporal variability of the ocean.

6.5 SWOT Surface Water Error Budget Validation

In this section we describe how the overall surface water performance of SWOT will be validated. We discuss how each contributor to the error budget will be validated independently.

The surface water performance of SWOT will be validated with a combination of measurements from *in situ* instruments and airborne instruments, including AirSWOT, during and after the end of the fast sampling phase.

The validation sites will be distributed to characterize the effects of uncalibrated phase/roll drift in the interior of continents, as well as a variety of lake, river, and wetland characteristics, including size, topography, and vegetation type. Validation sites will be divided into two types: Tier 1 sites that will involve direct field measurements by SWOT validation team members and Tier 2 site that will leverage existing measurement assets with minimal additional field measurements (e.g. USGS stream gauges) and will be used to estimate the spatial and temporal variability in SWOT measurements. There will be a total of about 15 Tier 1 sites (see Sections 7.2.1–7.2.4) and ~100 Tier 2 sites (see Section 7.2.5).

In situ observations of lake and river level and slope will be obtained at Tier 1 and Tier 2 sites with GPS observations in combination with temporal variations measured by existing river gauges, and/or temporarily installed pressure transducers and discharge gauges. The lake and river surface area will be measured using the AirSWOT near-infrared camera (or a similar system on a different airborne platform) at the same time as a SWOT pass. *In situ* information will also be collected regarding vegetation distribution, height, and canopy characteristics (Leaf Area Index (LAI), canopy closure), as well as a high accuracy digital elevation model of the surrounding topography for layover studies.

These measurements will enable the validation of SWOT elevation and surface water extent on a continental basis. The validation period used to assess mission success will take place during the first six months to a year of the start of the nominal mission phase, but validation will continue throughout the lifetime of the mission.

In this section we describe how each individual component of the surface water SWOT error budget will be validated.

6.5.1 Random height error validation

The random height error for hydrology targets can be assessed by simply examining the standard deviation of the SWOT height estimates over areas that are sufficiently large (for example, large lakes that are free from layover). Comparison of the noise statistics between LR and HR data (allowing for differences in random error performance due to presumming) can also validate the HR random error performance. Data from smaller water bodies will also be aggregated, with models used to aggregate the data statistically, to assess random-error performance.

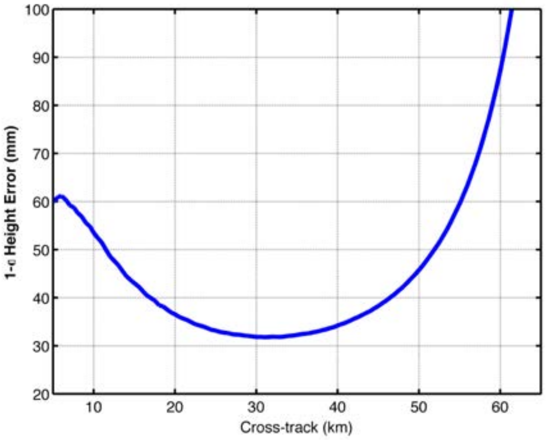


Figure 19. Random error as a function of the cross-track position (HR product). From JPL D-79084.

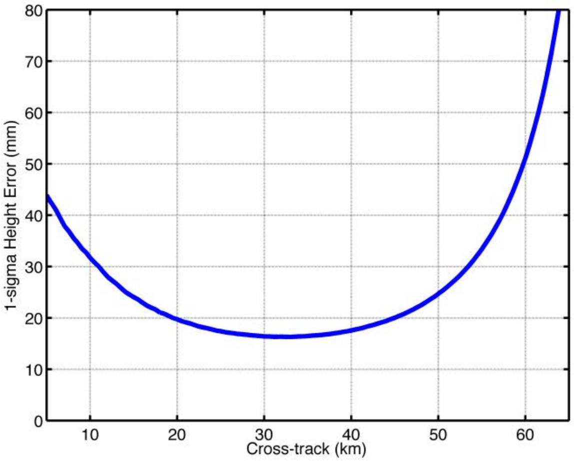


Figure 20. Random error as a function of the cross-track position (LR product). From JPL D-79084.

6.5.2 Absolute inland surface water height validation

The validation of the absolute heights requires that the absolute height of the surface of the considered water body is measured independently of SWOT. Several protocols will be implemented and will vary between Tier 1 and Tier 2 sites. The following sections (6.5.2.1 to 6.5.2.4) describe the various methods by which absolute height will be validated.

6.5.2.1 Absolute water height validation by pressure transducers

Dense networks of GNSS-leveled pressure transducers or GPS buoys will be installed along rivers and in lakes within the Cal/Val sites detailed in section 7.2. For rivers, transducers will be installed every 6-20 river widths; for small lakes, one transducer will be sufficient; for large lakes, five to ten transducers (located at different shoreline locations and in the lake center) will be used. These networks will allow validation of absolute SWOT height variations in space and time over short length scales. Comparison between SWOT heights and water absolute levels will be performed over a long period of time, starting during the 1 day orbit and continuing for at least one year during the nominal orbit.

A key issue to resolve for use of this method will be water surface curvature, for both rivers and lakes. For rivers, if we can assume that any curvature of the water surface long profile is below the detection limit of SWOT data then a single point measurement in the middle of a reach will characterize the average water surface height over the reach that SWOT will measure. In other words, if we can assume a linear water surface slope then our measurement task is greatly simplified. Pre-launch assessments will need to be made at each of the Tier 1 river sites to determine that they do not show significant long profile slope changes with variations in stage that may preclude the use of this option.

For small lakes, curvature effects are likely to be small (i.e. smaller than the SWOT detection limit) and can be minimized by positioning pressure transducers or GPS buoys at lake centers. For large lakes, the requirement is for pressure transducers or GPS buoys to be positioned at least 1km away from the shore such that any water height variation over the ~1km^2 SWOT averaging window has a linear slope. This will ensure that the point water height measurement is equivalent to an average of ground-based water height measurements over the SWOT averaging window. Pre-launch assessment will need to be made at large lakes to collect data on possible water height variation and length and height scales of water slope curvature. This will be achieved via an installation of five to ten pressure transducers around the perimeter of the lake.

For rivers, the existence of significant cross channel elevation changes (for example due to hydrodynamic super-elevation of the water surface) at the Tier 1 sites also need to be discounted as this would otherwise suggest that point elevation measurements of water height would have bias. A pre-launch field campaign is required at the river sites to measure the scale of such effects and determine whether or not these will be smaller than the SWOT detection limit.

Past AirSWOT data can also be used to examine for the presence of all the above effects, and this will be an immediate task for pre-launch activities.

6.5.2.2 Direct measurement of the free surface height at the exact timing of SWOT over passing

Direct measurement of water height at the time of SWOT over passing will be performed by means of GNSS systems, mostly based on the US GPS system. Several devices with floating GPS antennas currently are being developed and tested by the SWOT science team. The most advanced consists of a floating sheet of ~10m^2 bearing a GPS antenna for which height and attitude is continuously monitored (CalNaGeo, https://swot.jpl.nasa.gov/docs/jun17_stm_101_seine.pdf). Light and easy to set up, this equipment can be used to perform the mapping of several km^2 within a few hours. Other systems include GPS floats mounted on Sontek hydroboards coincident with Acoustic Doppler Current Profiler (ADCP) measurements. Prior to launch, comparisons will be made between the accuracy of GPS measurements likely to be obtained from all GPS measurement platforms. The sites to be measured this way will be selected among the official Cal/Val sites of the project, preferentially sites that will be over flown during the 1 day orbit

6.5.2.3 Absolute water height validation from Hydroweb/Hysope

External validation of the nadir altimeter and KaRIN products will be delivered in near real time by the Hydroweb/Hysope network over large global lakes with an accuracy of water level at sub-decimeter level reported continuously during the mission lifetime (Hydroweb: http://www.legos.obs-mip.fr/en/soa/hydrologie/hydroweb/; Hysope: http://hydroweb.theia-land.fr/?lang=en&). The Hydroweb and Hysope sites already are used for external validation by altimeter missions. The quality check of the nadir altimetry products is done using a set of in situ lake level collected through national hydrological services in USA, in Russia, in Chile, and in Argentina.

Figure 21. The CalNaGeo instrument used to produce the highest precision water surface elevations from GNSS measurements.

The required accuracy for the absolute surface water height validation is an absolute vertical accuracy to ±5cm at 1σ (minimum) or ±2cm at 1σ (target). Cal/Val sites where absolute surface water height measurements will be performed include all of the Tier 1 sites. These include sites over Rivers, Lakes, Wetlands and Estuaries.

6.5.2.4 Absolute water height validation using Tier 2 Cal/Val sites

In addition to the above methods, we will develop a network of Tier 2 Cal/Val sites where we will leverage existing gauge measurements of stage and discharge, and will add a GNSS-levelling of the gage datum. Once the reference point of the gauge is leveled to GNSS accuracy, the water levels recorded by the gauge (either manually or automatically) can be converted into absolute heights, directly comparable with the SWOT measurements in close vicinity. We plan to acquire a global database of a few hundred leveled gauges by launch. The countries where this work is already in good progress are the USA, France and the countries sharing the Amazon basin. Extension of this database to South Asia countries (India, Bangladesh, etc …), African countries (Niger, Congo, RDC) and European countries will be performed according to opportunity.

The Tier 2 Cal/Val network optimally will consist of ~200-300 sites with good global coverage of different hydroclimatic and ecosystem zones. Each gage will be levelled to have a required minimum vertical accuracy to ±5cm at 1σ (minimum) or ±2cm at 1σ (target).

Figure 22. The Sontek hydroboard system that will also be used to produce precision GPS measurements of water surface elevation.

6.5.3 Inundated surface area validation

6.5.3.1 River inundated surface area validation

To validate that SWOT can measure inundated area in rivers with sufficient accuracy to meet requirements presented in the SWOT Science Requirements Document, we will validate river inundated surface area using one or more of the following three methods, all of which will be evaluated in detail during prelaunch activities:

1. To directly validate inundation extent in rivers, we will acquire once at each Tier 1 field site a high-resolution (~1 m resolution) airborne dataset of near-infrared or mid-infrared photography (equivalent to Landsat TM band 4 or, ideally, band 5). This type of data currently is being collected using the AirSWOT Color Infrared (CIR) Camera, which will be evaluated for suitability based on flights conducted in 2015 and 2017. The airborne imagery must be acquired simultaneous to a SWOT overpass (<3 hrs different, but depending on the water dynamic on each site) during clear-sky conditions in order to provide a direct

comparison. There is a long heritage of measuring inundation extent using this type of imagery in rivers. See Figure 23 for an example of such imagery, acquired over the Tanana River in summer 2015.

2. To indirectly validate inundation extent in rivers, we will use the intersection of a high-quality topographic DEM and field measurements of surface-water elevation collected from either installed pressure transducers or from boat-measurements. While this validation method has the advantage that it does not require direct measurements of inundation coincident with AirSWOT, it does not provide direct measures of inundation extent.
3. During field campaigns to be conducted during both the fast sampling and nominal orbits, field Cal/Val teams will walk selected sections of water/land boundaries (shoreline) using GPS with <2 m horizontal precision in order to provide validation. This second step will be particularly critical to perform in areas with large, wet sand bars adjacent to sediment-laden rivers, as these features can look very similar in near-IR photography.

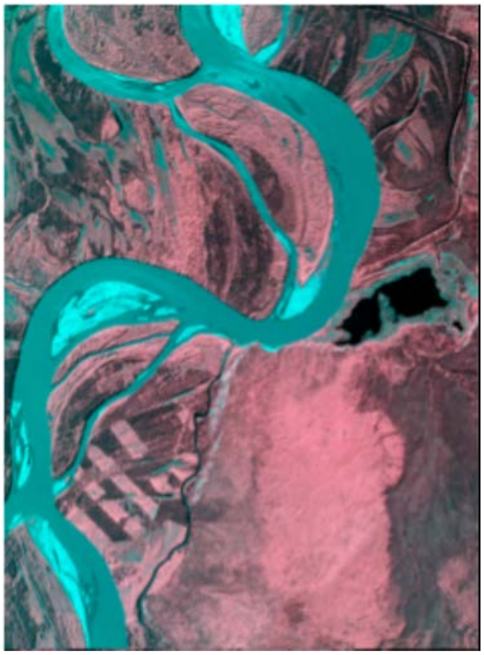


Figure 23. Example of color infrared photography acquired over the Tanana River, Alaska during summer, 2015. This type of imagery will be used to validate SWOT measurements of inundation extent in rivers.

The Cal/Val Tier 1 river sites where inundated surface area will be validated include: Willamette River, Tanana River, Mississippi River, Connecticut River, Garonne River, and a tropical river. The required image accuracy for inundated extent is 7.5% (minimum) and 1.5% (target) over a 1 km^2 area. For GPS surveys of inundation extent, we require horizontal measurement accuracy equal to ½ of the SWOT pixel size in the range direction (~12.5 m in the middle of the swath, minimum) and 1/10 of the SWOT pixel size, or ~2.5 m (ideal).

6.5.3.2 Small Lake inundated surface area validation

The ability of SWOT to meet the science requirements for inundation extent in lakes will be validated using one or more of the same three methods described above for rivers:

1. To directly validate inundation extent in small lakes, we will acquire once at each Tier 1 field site a high-resolution (~1 m resolution) airborne dataset of near-infrared or mid-infrared

photography (equivalent to Landsat TM band 4 or, ideally, band 5). The airborne imagery must be acquired simultaneous to a SWOT overpass (same day) during clear-sky conditions in order to provide a direct comparison. There is a long heritage of measuring inundation extent using this type of imagery in small lakes.

2. We will leverage relationships between lake height and inundation extent to predict inundation extent, which will then be directly compared to SWOT measurements. The relationship between height and surface area in most small lakes does not vary substantially as long as the shoreline does not change. In lakes that do not have highly variable shoreline characteristics, we will validate the inundation extent using a combination of a high-resolution digital elevation model (e.g. lidar) and measurements of water surface elevation. While this validation method has the advantage that it does not require direct measurements of inundation coincident with SWOT, it does not provide direct measures of inundation extent.
3. During field campaigns to be conducted during both the fast sampling and nominal orbits, field Cal/Val teams will walk selected sections of water/land boundaries (shorelines) using GPS with <2 m horizontal precision in order to provide validation.

Small lake inundated surface area will be validated at all Tier 1 small lake sites. The images of inundation extent should be accurate to 7.5% (minimum) and 1.5% (target) over a 1 km^2 area. For GPS surveys of inundation extent, we require horizontal measurement accuracy equal to ½ of the SWOT pixel size in the range direction (~12.5 m in the middle of the swath, minimum) and 1/10 of the SWOT pixel size, or 2.5 m (ideal).

6.5.3.3 Large lake inundated surface area validation

Measurement of inundation extent for large lakes will have different types of complexity than will validation of small lake inundation extent measurements. Most small lakes will be measured via a single SWOT overpass, while many large lakes will only be partially observed in any given overpass. It will not be practical to acquire airborne imagery over large areas directly coincident with SWOT overpasses. However, the large lakes chosen to be primary validation sites do not vary substantially in surface area over short time periods. Moreover, it is expected that it will be much easier to meet the SWOT inundated area accuracy requirement for large lakes than for small lakes simply because a much larger fraction of their area is distant from land contamination. As such, the following three measurement strategies will be used, neither of which requires acquisition of new datasets by the SWOT mission:

1. High- to moderate-resolution satellite imagery (e.g. Sentinel 2, Landsat) will be acquired close in time to SWOT overpasses, and inundation extent derived using existing methods (e.g. Li and Sheng, 2012) will be directly compared to SWOT-derived inundation extent.
2. Bathymetry of shallow lakes acquired using existing altimeters or in situ measurements of height and high-resolution images of inundation extent will be used to develop precise rating curves between inundation extent and elevation. These rating curves will allow precise estimation of inundation extent given knowledge of water surface elevation during the SWOT Cal/Val phase. Please see the case study on Lake Poopo described below.
3. Finally, inundated areas derived from rating curves developed between inundation extent and water surface elevation derived from existing altimetry resources will be compared against SWOT measurements for a variety of large lakes globally (e.g. Figure 24). A set of about 100 lakes among them half located on the Tibetan Plateau already exist (LEGOS work for Hydroweb database) and will be completed before the launch. This will serve as an

external source of validation for water extent validation although not strictly of land/water classification. If water height is validated by other means, then for each water height measured, a water extent can be calculated using polygon coefficients of the hypsometry curve and compared to the surface extent directly measured by SWOT.

The Tier 1 Cal/Val large lake sites where the inundated surface area will be validated include: Lake Issykkul, Lake Tahoe, and the large global lakes dataset (Hydroweb). The required accuracy of the inundation extent should be accurate to 7.5% (minimum) and 1.5% (target) over a 1 km^2 area.

Lake Poopo Case Study: In 2014, a DEM of the Lake Poopo, which is located over the Altiplano in South America, was developed using a combination of satellite imagery (set of landsat images) and laser altimetry on Icesat. Lake Poopo is very shallow, with high seasonal and inter-annual areal extent (and height) variability. Every year in winter, it is inundated and during the rest of the year it shrinks due to very high evaporation. At inter-annual time scales, this cycle of inundation and drought also is very unstable, with some very wet years contrasting with very dry ones (see Figure 25). In consequence, the derived DEM of Lake Poopo is valid from a minimum surface close to the full drought to a maximum when the lake is almost entirely inundated (red lines on Figure 25). The precision of this DEM has been established at better than 10 cm. It therefore can be used for validation of lake surface extent. For each water extent measured by SWOT, we can simply project the corresponding water mask to the DEM and determine the closest theoretical mask deduced from the DEM alone. Repeating this procedure pass after pass will give quantitative validation of water mask inferred from SWOT measurements.

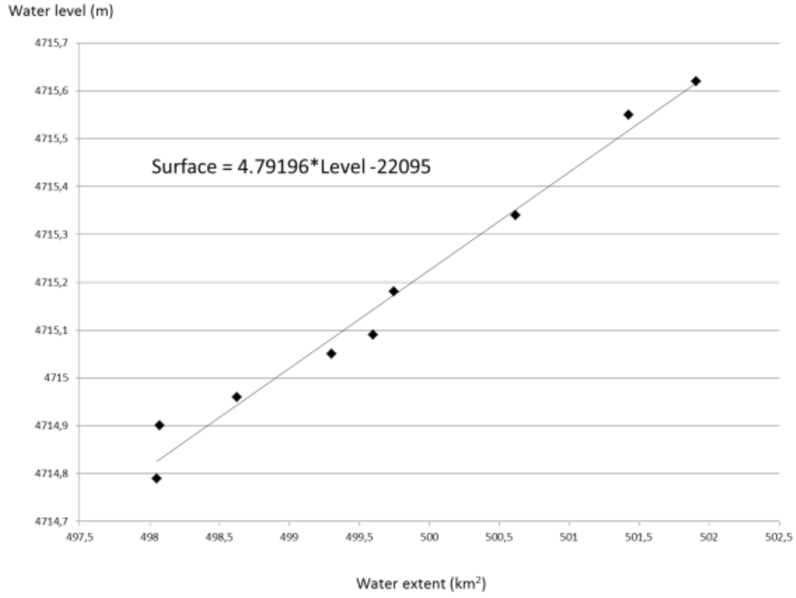


Figure 24. Hypsometry curve for the Lake Nganga-Ringco (Tibetan Plateau).

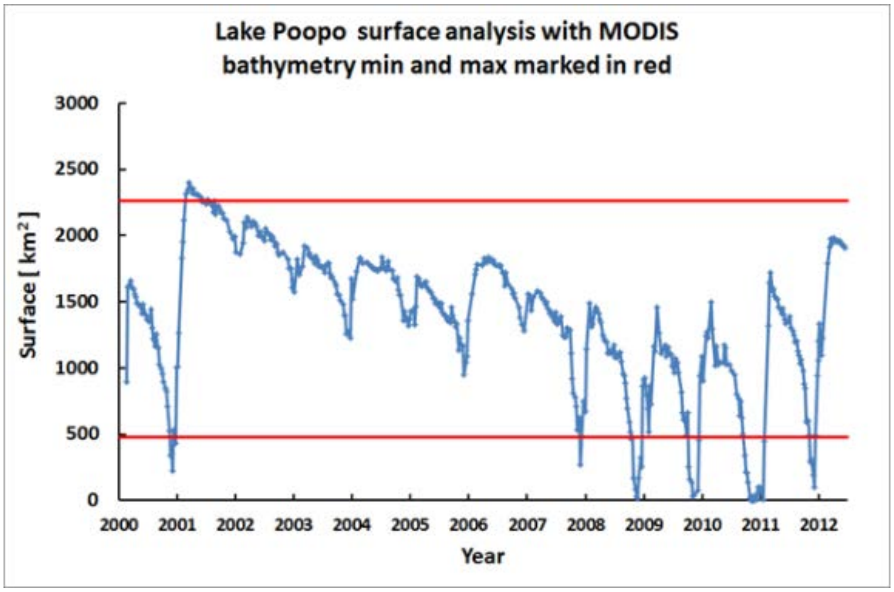


Figure 25. Lake Poopo surface extent measured by Modis from 2000 to 2012 every 8 days

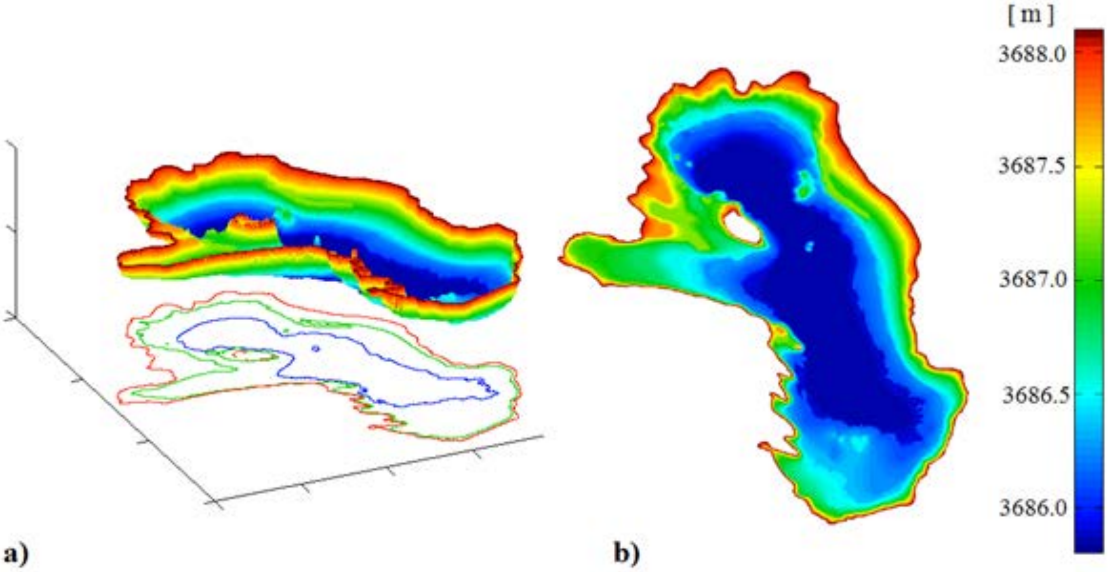


Figure 26. Image of the bathymetry of the lake Poopo.

6.5.3.4 Wetland inundated surface area validation

SWOT measurement of wetland surface area will be validated using one or more of the following four methods:

1. There is substantial precedent for measuring inundation extent under even very dense vegetation using L-band SAR sensors. Inundation extent will be measured at high spatial by the UAVSAR system, a JPL facility, concurrent with SWOT overpasses of at least two of the Lower Mississippi, Everglades, and Yukon Flats Tier 1 field sites. The resulting UAVSAR

inundation heights will then be compared directly against SWOT returns to assess SWOT performance in wetlands over a variety of vegetation types.

2. Various satellite sensors capable of measuring inundation extent in vegetated environments at high resolution may be available concurrent with SWOT during the Cal/Val phase, including Sentinel 1, NISAR, and future RADARSAT and ALOS missions. Although this method will not be our primary means of validating SWOT, it will allow greater geographic diversity in the types of wetlands validated.
3. We will use high-resolution lidar DEMs of wetland topography, where available, to assess inundation extent based on variations in water surface elevation measured from SWOT. This method has the advantage that it does not depend on simultaneous image acquisition with a SWOT overflight, though it does require a priori collection of a lidar DEM.
4. To understand the influence of vegetation on SWOT inundation extent and water surface elevation returns, we will collect airborne lidar measurements including both water surface elevation and vegetation height simultaneously with UAVSAR and SWOT measurements over at least two of the Lower Mississippi, Everglades, and Yukon Flats field sites. These measurements will allow us to assess vegetation height and canopy closure in a way not possible using ground-based measurements and will allow full understanding of SWOT capabilities in wetlands.

The Tier 1 wetland Cal/Val sites where inundated surface area will be validated include the Lower Mississippi, Yukon Flats, and Everglades. French sites will be selected later. The required accuracy of the external validation method is such that at least one method must have accuracy of at least 7.5% over 1 km^2, with an ideal accuracy of 1.5% over 1 km^2.

6.5.4 Range drift validation

The absolute range drift of KaRIn will be validated by comparison to nadir altimeter data over the ocean, as described in previous sections on long-wavelength ocean validation.

6.5.5 Roll/phase drift validation

Over land, the roll will be validated over lakes. A database of large lakes whose surface is not subject to rapid tilts (established from ongoing altimetry missions) is being built. These surfaces will be used as a reference to infer cross track tilts due to rolling. Thanks to the repeat orbit of the SWOT altimeter, we may calculate a mean vertical profile along each of the tracks for each chosen lake. In this process we benefit from the long-term time series of altimetry data since the launch of TOPEX/Poseidon. For each lake, although absolute height is changing due to hydrology, the relative height between each track shouldn't change from one cycle to another, except if seiches are observed. The same approach could also be used over major rivers where the mean slope is known with a good accuracy.

6.5.6 Land Wet-Tropo Delay Validation

The wet troposphere estimates over land are based on models. The models can be validated by comparison to radiometer, radiosonde, and GPS measurements. For large lakes, the models can also be compared to the SWOT radiometer data.

6.5.7 Other propagation delay validation

Ionosphere model corrections can be validated by comparison to local GPS estimates. Dry troposphere estimates are based on ECMWF models and have been reasonably well validated already.

6.5.8 Slope validation

Validation of the river slope requirement requires that the absolute height of the surface of the considered water body is measured independently of SWOT. Several protocols will be implemented, and these will vary between Tier 1 and Tier 2 sites. At the Cal/Val sites the following measurements will be made:

1- Dense networks of leveled pressure transducers or GPS buoys will be installed along rivers within the project calibration/validation sites detailed in section 7. River measurements are required approximately every 10 river widths over a length of at least 50 km. U.S. locations will include the Willamette River, Tanana River, Connecticut River, and Mississippi River. These networks will allow validation of SWOT slope variations in space and time over short length scales. Comparison between SWOT heights and water absolute levels will be performed over a long period of time, starting during the 1 day orbit and continuing for at least one year during the nominal orbit.

For large rivers (principally the Mississippi) the existence of significant cross channel elevation changes (for example due to hydrodynamic super-elevation of the water surface) at the Tier 1 sites also need to be discounted as this would otherwise mean that slope measurements would vary substantially depending on which side of the river they were obtained from. A pre-launch field campaign is required at the large river sites to measure the scale of such effects and determine whether or not there are going to be smaller than the SWOT detection limit.

2- Direct measurement of the free surface height at the exact timing of SWOT over passing. Such measurements will be performed by means of GNSS systems, mostly based on the US GPS system. Several types of GPS floats are currently in use by the group (see section 6.5.2.2). In situ measurements of slope will be made at least twice at different discharges for all Tier 1 sites using this method coincident with SWOT overpasses during the cal/val phase of the mission.

3- While the two methods above are capable of measuring slopes over relatively short river reaches, they are not capable of synoptically measuring slopes over long river reaches (e.g. >100 km). The only tool currently capable of validating such slopes derived from SWOT is AirSWOT (Icesat2 could provide additional inputs but this mission is not yet launched). As such, AirSWOT will serve as a crucial tool for validating SWOT slope measurements. AirSWOT will be flown at least twice over the Willamette, Mississippi, and Connecticut Rivers at different discharges during the cal/val phase in order to validate SWOT slope values over long reaches.

4- At Tier 2 sites, pairs of accurately leveled gauges will provide estimates of water surface slope between them, though not with the degree of fidelity provided by the previous three methods. Nonetheless, these sites will be used to validate SWOT slope in environments where SWOT-dedicated measurements are not feasible due to cost or logistical difficulties.

The Cal/Val river sites where slope will be validated include Tier 2 river sites and the following Tier 1 sites: Willamette, Connecticut, Tanana, Mississippi, and Garonne Rivers. The required accuracy of the independent slope measurements (from AirSWOT, pressure transducer arrays, and GPS drifters) should be at least 8.5 μrad (minimum) and preferably as good as 1.7 μrad (ideal).

6.5.9 Layover flagging and impact validation

The impact of layover on height and slope estimates will be characterized by comparison to truth measurements as described in previous sections. The contributions due to layover will be separated from other contributors by comparison to predictions using high-fidelity DEMs and models of sigma0, which can be informed by airborne Ka-band reflectivity estimates. A geometric flagging assessment only requires the use of a high-fidelity DEM.

6.5.10 Rain flag validation

The rain flag is designed to alert users to the presence of rain during measurements, which can compromise SWOT performance. There are several ways in which the presence of rain will be validated. First, for Tier I field sites at least, local met stations will be erected, and these stations should include tipping buckets or other means of precipitation measurement. This direct measurement at the site will give the time and intensity of rain events for validation. Second, commercial Doppler radar is effective at detecting rain events, and many civilian and government websites allow users to view and download Doppler images. In the case of a rain flag without an in situ met station, these Doppler maps will be used to verify the presence and intensity of rain. Finally, there are several satellite products (e.g. the Global Precipitation Mission) that identify rain events, although these products are far less reliable than in situ measurements or local Doppler radar. These products will be used to validate the rain flag in cases where the primary two validation measurements are unavailable.

6.5.11 Ice flag validation

The SWOT ice flag is designed to indicate where and when SWOT-observable water bodies are covered with snow and ice. Ice flagging will be nominally based upon the use of optical satellite imagery, which can robustly differentiate ice and water at a range of spatial resolutions. We will use daily moderate-resolution images from MODIS and/or VIIRS to detect ice breakup timing in the pan-Arctic region (where the majority of river and lake ice occurs). We will use higher-resolution imagery (e.g. Landsat, Sentinel 2, ASTER) to assess the detailed patterns of SWOT ice flag accuracy during breakup and validate the ice flags. However, because SWOT and these optical imagers will not be in synchronous orbits, it will be possible to validate the ice flag using space-based assets alone only at the reach scale. In order to validate pixel-scale flags, we will obtain airborne optical imagery of a portion of the Tanana River, Alaska coincident with SWOT overflights during and before ice breakup. Ice cover will be mapped using both SWOT and the optical imagery, and the results will be compared.

6.5.12 Land flag validation

The SWOT land flag is designed for objects that give a reasonably bright radar return but that are not water, and are thus commission classification errors. In essence the land flag is the inverse of the water mask, and will be validated in the same way. However, validation of lake and river inundated area will leverage other radars that may have similar commission issues as SWOT. Therefore, validation of land flagged products will rely primarily on aerial and satellite imagery and in situ GPS maps of water extent where available. The only additional resources required for this validation will be staff time to check each land flag object, as the in situ data and imagery required for validation will be collected for other purposes.

6.5.13 Geolocation validation

There is a tradeoff between the geolocation accuracy and spatial precision of SWOT data. To ensure that SWOT products meet the geolocation science requirement (2.6.3a), comparison of their SWOT-derived position will be made against position data of known precision. Since SWOT data will have irregular spacing, geolocation validation must be performed on a pixel by pixel basis, and validation will be performed for distinct targets that are easily identified. Ideally, this validation will be made using precise GPS coordinates of the corner reflectors already deployed at Tier I field sites. Other targets for geolocation validation will be determined based on the site conditions at each cal/val site, and appropriate objects that can reliably be detected in SWOT data should be identified and their GPS positions recorded. In the cases where these objects cannot be found in the field, aerial or satellite imagery should be obtained to cross reference SWOT data and geolocation error determined from these products.

6.6 Surface Water Data Product Validation

In addition to the validation of each component of SWOT's surface water error budget (section 6.5), the main parameters of the Level-2 hydrology products will be validated. In many cases, the data product validation will take place concurrently with error budget validation. When this is the case, it will be noted below.

6.6.1 Pixel cloud product validation

The SWOT pixel cloud product is a level 2 product intended to provide access to height, water/land classification, and relevant quality flags in their rawest form. It will include both geolocated and slant/range coordinates and will be the basis for development of raster and vector products described below. There is no independent requirement on pixel cloud height accuracy that is different from the overall height requirements described in section 6.4.2. As such, we will validate heights in the pixel cloud by comparing spatial averages of pixel heights within a water body at relevant scales of $(250\ \text{m})^2$ and $1\ \text{km}^2$ against field measurements of height collected as described in section6.5.2. Similarly, we will validate classification accuracy against measurements from airborne infrared imagery available at substantially higher resolution than SWOT. We will focus on validating inundation extent classification accuracy at SWOT-relevant scales described above for height. Other quantities, including ice, rain, and layover flags, will be validated on a pixel-by-pixel basis as described in section6.5.

6.6.2 River vector product validation

Pass-based vector data product for rivers

Pass-based river vector products will include point, line, and/or polygon features that are derived from the pixel cloud of just one SWOT overpass. They will be the primary repository for reach-scale height, slope, width/inundation extent, and discharge data on rivers. Unlike the raw pixel cloud product, the vector product will have already aggregated SWOT height and classification data into defined reaches. Values for height, slope, and inundation extent in these reaches will be validated using methods described in Sections 6.5.2, 6.5.3, and 6.5.8. However, the successful translation of SWOT data from pixel cloud to reach will also be evaluated. We will compare the flow length of reaches derived from SWOT data with similar reaches derived from high-resolution airborne (e.g. AirSWOT) or satellite (e.g. SPOT, WorldView) imagery over Tier 1 validation sites including the

Willamette, Garonne, Connecticut, and Tanana Rivers. This comparison will be critically important for understanding the error characteristics of SWOT-derived slope, which depends on the accuracy of both SWOT-derived heights and the length of the river reach. We will directly compare slopes in the pass-based vector products against slopes measured *in situ*, as described in section 6.5.8. We will also compare reach-averaged heights and inundation extents against manually aggregated values from the pixel cloud product and field-measured values at Tier 1 sites in order to ensure consistency.

Cycle-based vector data product for rivers

In addition to producing pass-based vector products, vector products will also be created that incorporate data from an entire SWOT orbit cycle (21 days). Unlike pass-based products, these cycle-based products often cannot be effectively evaluated against instantaneous measurements of height, slope, inundated area, and other quantities. In the case of height and slope, we will rely on existing stream gauges and the installation of networks of temporary gauges that will measure water surface elevation every 15 minutes (or less), as described in sections 6.5.2 and6.5.8. Validation of cycle-based inundation extent will be more complex, as there is no feasible method of directly observing variations over a 21-day timeframe. Instead, for Tier 1 sites with high-quality bathymetric DEMs we will use inundation extent-stage rating curves as described in section 6.5.3.

6.6.3 Lake vector product validation

Pass-based vector data product for lakes

Pass-based lake vector products will consist of polygons derived from the pixel cloud product representing lake boundaries. They will be the primary repository for whole-lake values of height, inundation extent, and relevant quality flags. Unlike the raw pixel cloud product, the vector product will have already aggregated SWOT height and classification data. Values for height and inundation extent for whole lakes will be validated using methods described in Sections 6.5.2, 6.5.3, and 6.5.8. However, the successful translation of SWOT data from pixel cloud to whole lake will also be evaluated. We will compare the inundated areas and boundaries of lakes derived from SWOT data with similar values derived from high-resolution airborne (e.g. AirSWOT) or satellite (e.g. SPOT, WorldView) imagery over Tier 1 validation sites including Lake Tahoe, the Prairie Potholes, the Yukon Flats, mountain lakes in California, and other targets as described in Section 6.5.3. We will also compare whole-lake heights and inundated areas against manually aggregated values from the pixel cloud product and field-measured values at Tier 1 sites in order to ensure consistency.

Cycle-based vector data product for lakes

In addition to producing pass-based vector products, lake vector products will also be created that incorporate data from an entire SWOT orbit cycle (21 days). Unlike pass-based products, these cycle-based products often cannot be effectively evaluated against instantaneous measurements of height and inundated area. In the case of height, we will rely on the installation of networks of temporary gauges that will measure water surface elevation every 15 minutes (or less), as described in section 6.5.2. Validation of cycle-based inundation extent will be more complex, as there is no feasible method of directly observing variations over a 21-day timeframe. Instead, for Tier 1 sites with high-quality bathymetric DEMs we will used inundation extent-stage rating curves as described in section6.5.3.

6.6.4 Raster product validation

A method will be provided to generate a pass-based raster product from the pixel cloud product at a range of spatial resolutions. This raster will include (at least) information on location, land/water classification, height, and brightness. We will validate the raster data product by comparing it to in situ and airborne data on height and inundation extent as discussed in sections 6.5.2 and 6.5.3.

6.7 Discharge Characterization

6.7.1 Characterization of derived bathymetry

A class of models currently available to derive discharge from a set of height, width and slope also needs a bathymetry of the river reach. When not available, this bathymetry is predicted together with the discharges. In the case when models of this kind is retained by the Discharge Working group for the estimate of SWOT discharge products, the bathymetry predicted by the algorithms will be characterized in the two following ways:

1. The bathymetry will be characterized by comparison with actual cross sections, mostly collected during ADCP measurements (see section 6.7.2). A database of such cross sections, preferably leveled, will be constituted. USGS possesses hundreds of thousands of such cross-sections that could be made available to the project, contingent upon USGS involvement. It would be preferable if these cross sections were leveled. Also, such a dataset of hundreds of cross sections exist for the Amazon basin, the lower part of the GBM (Gange- Brahmaputra,-Meghna) river system, the major Brazilian rivers, French and Italian rivers. It is already agreed that these cross sections will be made available and can be used by the project. We are aware that such cross sections exist for some rivers running in other South American and European countries but their integration into the database will be made only on a “best effort” basis, depending on the good will of the agencies possessing these data to provide them for free.
2. The SWOT bathymetry will be characterized by comparison with river bed elevations estimated from other independent sources, in particular from rating curves which use water depth to derive discharge (instead of the water elevations). A database of such virtual river bed elevations (VRBE, in opposition to bed elevations actually obtained by direct measurement) will be constituted. Scientific projects have already produced such a database in the Amazon basin. That for the Congo basin has been constituted in 2017, with an ongoing work on Niger river

6.7.2 Characterization of derived discharge

SWOT-derived discharge is a critical hydrology product expected to be of great interest to the international hydrology community. A primary purpose of the SWOT discharge product is to produce estimates in ungauged basins and in regions where current discharge knowledge is spatially discontinuous. While is by definition impossible to characterize a SWOT discharge product in these situations, discharge cal/val activities for rivers of known discharge are critically important for the mission as a whole.

Characterization of discharge is straightforward, and is performed by directly comparing SWOT derived-discharge to some known discharge. Objective characterization will be achieved by calculating a suite of metrics first proposed by Bjerklie et al., 2005. These metrics include the RMSE, RRMSE, model selection criteria (MSC), and the mean and standard deviation of each of the raw, relative, and log residuals between SWOT-derived and measured discharge. These metrics allow assessment of discharge bias, stability, and total error.

The characterization of discharge will be performed on the basis of:

1. the ST projects selected by the ROSES/TOSCA call.

2. The discharge algorithm(s) finally selected by the ST to be implemented in the production chain.

The primary Cal/Val activity for characterizing discharge is to produce a reference discharge against which SWOT may be compared. SWOT-derived discharge will be compared with discharge derived *in situ* by the Cal/Val team using the following methodologies:

6.7.2.1 Direct discharge measurement

Perhaps the most accurate and straightforward way to produce a reference discharge is by measuring discharge directly in the field at the time of a SWOT overpass. Today, the most up-to-date instrument to measure discharge is an ADCP with GNSS positioning. In the case that new technologies are available at the time of the launch, these will be utilized. ADCP instruments are expensive, and making spatially distributed measurements with them is time consuming (although orders of magnitude more efficient than previous technology). Therefore, this technique will be implemented at a very limited number of sites depending on the funding capabilities. The locations will be selected within the sites included in the list of official Tier 1 sites. During the 1-day phase, the measurements will be performed daily, as closely as possible to the time of over passing by SWOT (these cannot be exactly simultaneous since ADCP measurements can take at least one hour for larger rivers). During the nominal phase, in situ measurements will be made at the day of passing (e. g. twice per cycle) and should attempt to include a time window covering the largest and lowest flows (half of a hydrological cycle)

Resources required: The ROSES/TOSCA call will determine the personnel that will perform these measurements. For each discharge measurement in situ, funds are needed for personnel travel and lodging, and it is expected that teams will have access to or have requested funding for an ADCP. Additional funds are needed for watercraft and transportation of watercraft to the field sites.

6.7.2.2 Indirect discharge measurements

Considering the impracticality of directly measuring discharge at numerous world rivers, the Cal/Val team will leverage stream gauges and rating curves to produce reference discharge for numerous sites. Most of the discharge values published in the World's basins are derived from river gauges and a rating curve (RC, stage/discharge relationships), and these gauges can provide continuous estimates of discharge at a station. SWOT-derived discharge will be compared to these rated discharges at a list of sites established by the Science Team prior to the launch, and gauges will be used to characterize the discharge at different time scales (instantaneous discharge, seasonal mean, annual mean). Such RC are already available for thousands of USGS gauges, and the USGS should make them available to the project through a proposal at the ROSES call. Scientific projects are currently establishing such RC over a large variety of rivers (from the typical scales of 100m^3/s to 100,000 m^3/s) in the large basins (Amazon, Congo, GBM). This database will be made available to the project for the characterization of the SWOT product at a large scale.

Resources required: It is expected that these gauge data will be acquired via the public domain (in the US and France), by the USGS pending a ROSES proposal, or via existing and ongoing scientific work. However, for Tier 1 Cal/Val sites, gauges and rating curves should be established prior to launch within the target SWOT reaches. The instrumentation required to establish these gauges is identical to those needed for slope validation, so funding and schedule for these activities is identical to those listed in 6.5.8. Additional funding will be needed to make in situ measurements of discharge at these gauges prior to launch to establish the rating curve at each, and extra funds should be allocated to the slope validation installations so personnel can take the time to deploy and ADCP within the reach.

6.7.2.3 Model output

While field measurements and gauge estimation of discharge are highly respected and accurate means of producing reference discharge, hydraulic models are also able to produce discharge with good accuracy in many cases. At some of the ST sites (see for example the Garonne site in France), high accuracy hydraulic models have been developed and produce accurate discharge estimates given top-of-reach in situ inputs. These estimates will be used to characterize the SWOT products. The list of sites/models to be used this way will be established in agreement with the ST and the discharge Working Group. All models will be furnished by members of the ST, and any model development will occur in the frame of ROSES/TOSCA proposals.

6.7.2.4 Statistical/morphological estimates of discharge

Finally, the above methodologies are able to produce reference discharge for single channels with a fair degree of field labor or previous infrastructure development. Since SWOT estimates of discharge are perhaps of most interest in ungauged basins, classic morphological estimates of discharge will be used to broadly characterize discharge in these regions. It has long been established that mean discharges rely on the morphology of the river reaches (or, equivalently, that the morphology of a reach is forced by the amount of water that has to flow through it), in particular its mean depth, width and slope. At a global scale, the SWOT discharge will be characterized with respect to the existing rules of thumb. These standard practices include development of regional power laws between drainage area, width, depth, and slope of river channels. In these cases, the suite of metrics proposed by Bjkerlie et al. will not be used to characterize discharge, and characterization will be more qualitative as befits the nature of the reference discharge.

7 SWOT CAL/VAL SITES

This section describes the sites that will be instrumented by the SWOT project, ST members, or collaborating organizations, and how these Cal/Val sites will be used to accomplish the calibration and validation needs described above. It also outlines the pre-launch and post-launch activities that will be performed for each site.

The responsibility for maintenance of the Cal/Val sites will vary depending on the purpose of the site and the need for it to derive or validate parameters required by the SWOT project. In addition to US or French project supported sites, it is envisioned that community sites will be developed by the science team or be contributed by other agency or foreign partners. Below, we indicate the primary responsibility for each site, although sites can serve multiple purposes. We also propose to leverage existing Jason Cal/Val sites, supplementing their capabilities as necessary.

7.1 Ocean Cal/Val sites

Ocean Cal/Val sites are divided in two complementary categories: absolute range/SSH bias and relative 2D SSH and its derivatives (e.g. geostrophic currents). The former extensively leverages existing Cal/Val sites used over two decades for nadir altimeters and will monitor SWOT biases and trends in different regions during the 3-year nominal phase. The latter combines existing infrastructures and new measurement techniques during the fast-sampling phase and the nominal phase.

7.1.1 Validation of the absolute SSH bias

Over more than two decades of nadir altimetry Cal/Val, the ability of precise in situ Cal/Val to measure the local bias has been largely demonstrated. These techniques are complementary with global metrics (e.g. statistical or global in-situ networks). Having at least two or three absolute validation sites makes it possible for local/global comparisons to infer the influence of errors that depends on in-orbit and geophysics conditions (e.g. geoid, tides, corruption by coastal layover). To that extent, the ocean calibration sites described in this section feature provide a wide range of sea state and geographic conditions.

Note that neither the US (Harvest) nor French (Corsica) long-term calibration sites for absolute range biases will be observed during the fast sampling phase, but they will form a critical component of the long-term Cal/Val monitoring of SWOT performance during the science phase. The KaRIn swath will observe the Bass Strait (Australia) long-term calibration site during the fast sampling phase.

7.1.1.1 Harvest Cal/Val Site

7.1.1.1.1 Site Description

The Harvest Oil Platform (Figure 27) is located about 10 km off the coast of central California, near Vandenberg U. S. Air Force Base, the site for the upcoming Jason-3 launch. The platform is fixed to the sea floor and sits in about 200 m of water near the western entrance to the Santa Barbara Channel. Conditions at Harvest are typical of the open ocean: wind waves and swell average about 2 m, though waves up to 10 m have been experienced during powerful winter storms. Built in 1985 and operational since 1991, Harvest continues to serve as production platform, drawing oil and gas from the Arguello reservoir. Harvest has also served as the NASA prime calibration site for the TOPEX/POSEIDON (1992–2005), Jason-1 (2001–2013) and OSTM/Jason-2 (2008–) missions, and as such is an important international resource for the study of sea level from space. The Jason-3 (2016–)

and Jason-CS (2020–) missions will follow the same ground track, implying that Harvest will continue to serve a crucial role in validating data from precise spaceborne radar altimeter systems.

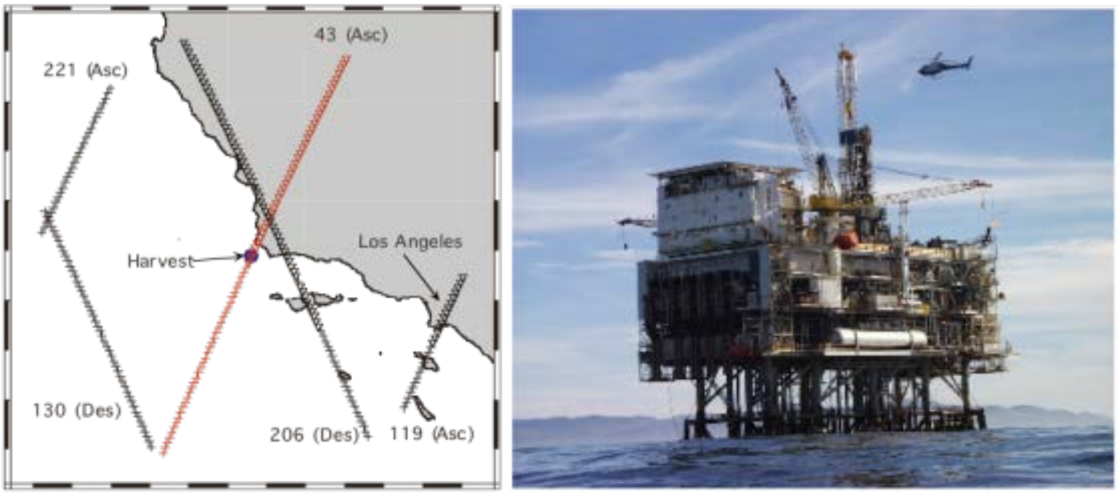


Figure 27. Map of Harvest Platform vicinity showing ground tracks for Jason reference missions (left). The platform (right) hosts one of the oldest tide gauge/GPS collocations in the world, and has provided for continuous monitoring and of the TOPEX/Poseidon and Jason series of reference missions since 1992.

Harvest offers a number of advantages as a spaceborne altimeter calibration site. The platform is located sufficiently far offshore so that the area illuminated by the traditional (pulse-limited) altimeter is covered entirely by ocean when the satellite is directly overhead. At the same time, the platform itself is small enough so that it does not have a meaningful influence on the reflected radar signal. Equally important, the open-ocean environment implies that the spacecraft measurement systems are monitored in the conditions under which they are designed to best operate.

7.1.1.1.2 Site Goals

The principal goal of the Harvest experiment is maintain this vital long-term calibration record, and to improve the skill with which the experiment can detect systematic errors in the altimeter measurement systems.

7.1.1.1.3 Site Instrumentation

The Harvest experiment features carefully designed collocations of space-geodetic and tide-gauge systems to support the absolute calibration of the altimetric sea-surface height (SSH). The primary tide gauge system is a dual-redundant Nitrogen Bubbler/pressure transducer from NOAA, which has provided continuous data (with a few short exceptions) since 1992. A lidar is operated by the University of Colorado, and two new radar gauges are slated for installation before Jason-3 launch. These competing technologies for measuring the water level will offer an unprecedented opportunity to characterize the systematic errors experienced in dynamic sea-state environments. The platform GPS station is one of the oldest continuously operating sites in the International GNSS Service (IGS) network. A new GPS station (and antenna) was installed at a different location on the platform in early 2015 to provide competing measurements of the platform subsidence and zenith wet troposphere path delay under different multipath conditions. The wealth of information from the Harvest experiment underscores the unique contributions of a dedicated, well-instrumented and continuously maintained calibration site. The platform sensors can be complemented by buoy campaigns for particular applications.

7.1.1.1.4 Pre-launch Site Characterization

Pre-launch activities will focus on adapting the Harvest experimental strategy to support the SWOT mission repeat ground track configuration. As shown in Figure 28, Harvest is not in the swath for the 1-d fast repeat phase of the SWOT mission. Regional calibration techniques (using, e.g., mean sea surface profiles), supplemental tide gauge and precision moored buoys are all candidates for bridging the gap from the open-ocean SWOT ground track to Harvest. We will in particular leverage the results from a current JPL/NOAA initiative to develop a prototype precision GPS buoy for long-duration monitoring of water level and atmospheric properties.

The nominal SWOT orbit has a ground track that passes very close to Harvest (Figure 29). This is very favorable approach from the open ocean (similar to that of the Jason reference missions), and will enable a robust determination of the bias of the SWOT nadir altimeter system against the backdrop of the TOPEX/Poseidon and Jason climate-scale calibration record from the platform. For this 21-d repeat, Harvest also lies in the swath of a descending pass (307), a geometric configuration that promises to lend new insights on the link from the nadir measurement to the swath.

7.1.1.1.5 Post-launch Cal/Val Activities

Post-launch activities will focus on the careful addition of SWOT data to the Harvest calibration record. We will also study techniques (e.g., relying on distributed buoys) to provide a joint calibration of the swath and nadir ground track as the calibration point is overflown.

Figure 28. Location of SWOT 1-d fast repeat swath tracks in relation to Harvest. The two bands outlined by the white lines depict the swath tracks.

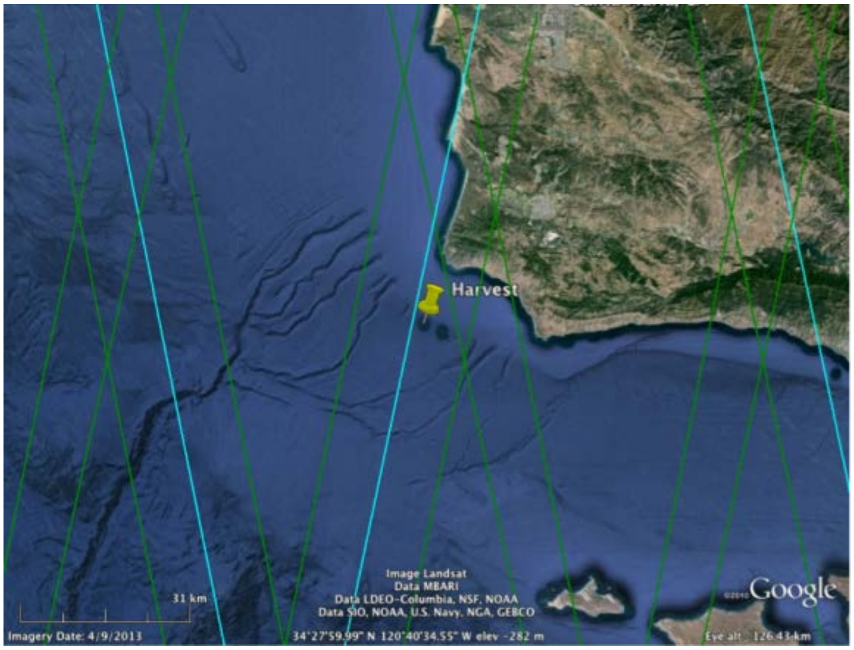


Figure 29. Location of SWOT 21-d repeat swath tracks in relation to Harvest. The blue line passing closest to Harvest is the ground track traced by the nadir point of ascending pass 294. Harvest is also in the swath of the descending pass 307.

7.1.1.2 Corsica Cal/Val Site

7.1.1.2.1 Site Description

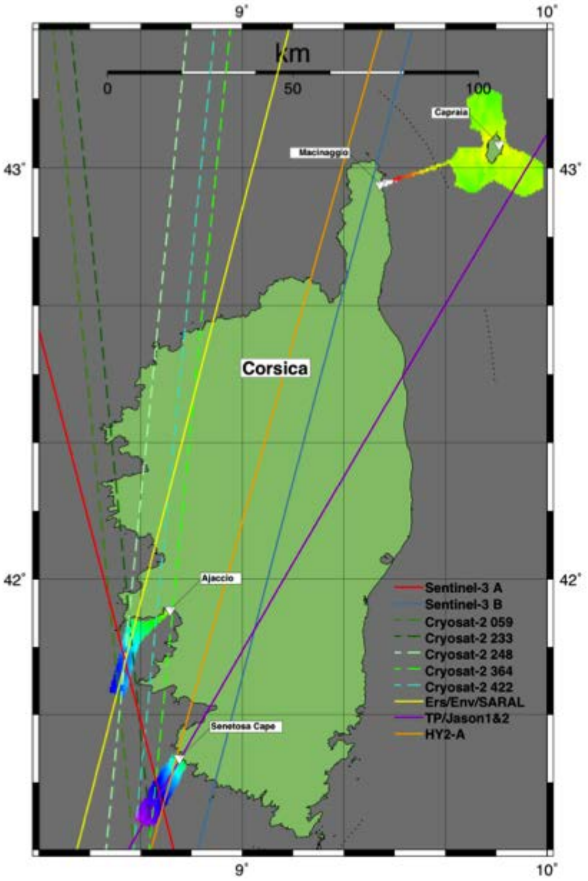


Figure 30. Configuration of the Corsica calibration site. The color contour maps correspond to the "local geoids"

The primary facilities for the Corsica calibration site have been operational at Senetosa since 1998 to monitor the TOPEX/Poseidon and Jason missions (Figure 30). The site was expanded to facilitate comparison at two additional comparison points, Ajaccio and Capraia, also adding the ability to monitor the Envisat and SARAL/AltiKa satellites. This provides a unique opportunity to cross calibrate all these disparate missions with common processes and standards. For example, the wet tropospheric path delays for comparison to the satellite radiometer estimates can be determined from GPS and ground-based meteorology stations located at both Ajaccio and Senetosa. The close proximity of each site also provides economic and logistical advantages, such as the ability to use to the same GPS-based sea level measurement systems to regularly perform independent calibrations at the various comparison points. An evolution of the "overhead" calibration methods to a regional approach has been also developed based on the extended Corsica site capabilities (Cancet et al. 2013; Jan et al. 2004).

7.1.1.2.2 Site Goals

The traditional "overhead" concept of in situ altimeter calibration involves the direct satellite overflight of a thoroughly instrumented experiment site. It is essential that such a calibration site has some means of observing sea level in situ (using for example a conventional tide gauge, ocean mooring or GPS-based sea level measurement systems) and subsequently tying the sea level estimates to a terrestrial reference frame comparable to the satellite altimeter. In an ideal situation, the experiment site is located on a repeating ground track (or better still a cross-over of an ascending and descending altimeter pass), sufficiently out in the open-ocean to avoid contamination of either the altimeter or radiometer footprints by the land. On the contrary, a coastal site such as Corsica can be used as a valuable tool to estimate the errors in altimetry when approaching the coast, either for the range itself or the associated corrections (Wet troposphere) as well as for Significant Wave Height.

Two distinct methodologies exist for the measurement of the in situ Sea Surface Height at a comparison point that is subsequently used for comparison against the altimeter SSH. The techniques and underlying algorithms are quite disparate depending on the particular application and will not be developed here (Bonnefond et al. 2011). However, it must generally consider — either directly or indirectly — geophysical, oceanographic and atmospheric phenomena that cause the variation in sea level over time and space.

<u>Direct method:</u> In this case, SSH is physically observed at a offshore comparison point using, for example, GPS-based systems or offshore instrumentation, as it is the case for the Harvest platform (Haines et al. 2003).

<u>Indirect method:</u> In this case, the SSH measurement involves the observation of sea level away from the comparison point, typically using a tide gauge at nearby (typically coastal) location. The offshore altimetric SSH is then “transferred” or “extrapolated” at the location of the in situ instrument through the use of precise regional geoid models, and in many cases, numerical tide models. Tidal models are not used in Corsica (especially at Senetosa) because the estimated impact, even using high-resolution models, is at the level of a few millimeters over the considered area (Cancet et al. 2013).
In the case of the Corsica experiment reported here, both direct and indirect methods are used. Thus, the local geoids built under the T/P and Jason ground track #085 at the Senetosa Cape (Bonnefond et al., 2003b), and under the Envisat and SARAL/AltiKa ground track #130 near Ajaccio are key components to imposing the datum for our absolute calibration process when using the indirect method. Details about the SSH bias processing ($SSH_{altimetry}$ – $SSH_{in\ situ}$) and the general parameters used are not recalled here but can be found in Bonnefond et al. (2003a , 2011 and 2015). In Corsica two independent instruments (tide gauge and GPS-based sea level measurement systems) are used with differences in terms of processing to compute the SSH bias.

As already planned, the 1-day orbit ground track is too far from Corsica to use any of the current instrumentations, so we will focus our Cal/Val activities to the nominal phase. If Corsica is selected to be overflown, Figure 25 illustrates the best scenario, using a descending track that pass over the 2 existing geoids respectively at Ajaccio and Senetosa sites. This should allow performing the Cal/Val for both nadir and swath. This configuration will permit to validate swath measurement in various situations: the right swath will be always in open-ocean conditions, while left swath will encounter coastal conditions and then permit to study the impact of land contamination (Bonnefond et al., 2015). Moreover, “Boussole” a buoy designed for Cal/Val of ocean color sensors (MERIS, SeaWiFS, and MODIS) is located in the right part of the swath (Antoine et al. 2008; http://www.obs-vlfr.fr/Boussole/html/home/home.php). This buoy (Figure 31 left) is maintained in the framework of Sentinel-3 mission by CNES and ESA and may be used to also to install dedicated instruments in the framework of SWOT mission.

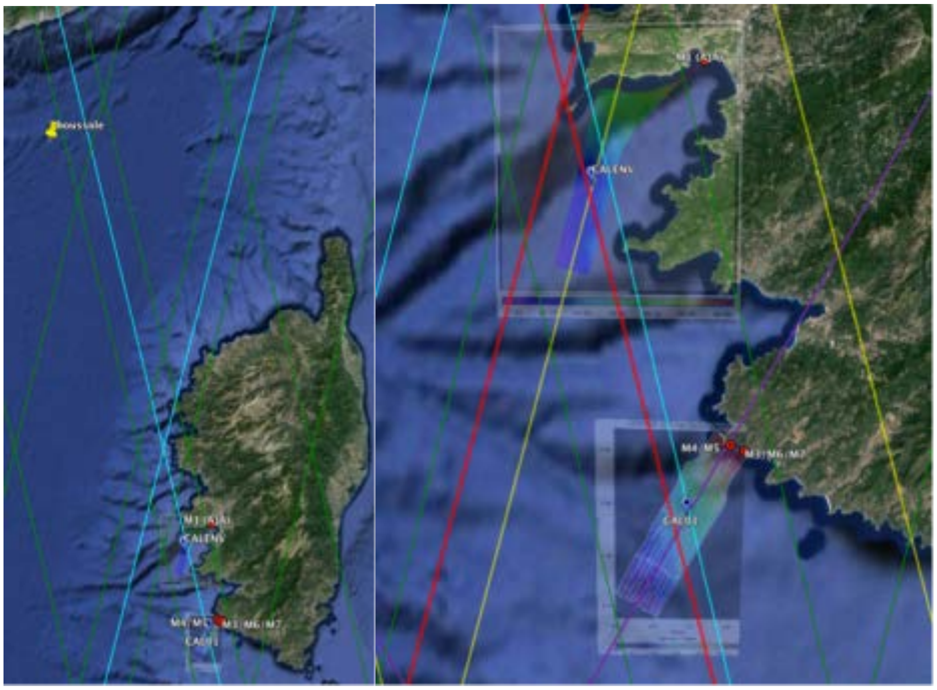


Figure 31. Possible location of SWOT ground track during the nominal phase. Left: overview with nadir light blue and swath limits in green. Right: zoom over Ajaccio and Senetosa sites with other mission ground tracks (red = Sentinel-3A, yellow = SARAL/AltiKa, Envisat, …, purple = T/P & Jasons)

7.1.1.2.3 Site Instrumentation

The Senetosa site is equipped with 4 tide gauges, located on each side of T/P and Jason ground track dedicated to the altimeter calibration process. A permanent GPS station is operational since 2003. Surveys of the geodetic markers and tide gauge locations have been undertaken regularly since 1998 and the repeatability of the GPS solutions and the optical leveling are below 1 cm and 5 mm respectively. At Ajaccio, a permanent GPS station (IGN) and an automatic radar tide gauge (SHOM) have been installed since 1999.

Since 2000, a GPS buoy has also been used in the calibration process at Corsica: the GPS buoy is deployed for ~1 hr surrounding overflights (~10 km offshore) whenever sea-state conditions are not too harsh to ensure safe navigation. Bonnefond et al. (2015) provide an example of where both the direct and indirect methodologies are combined. A major change has been implemented since 2012: the traditional waverider buoy was replaced by a zodiac (termed GPS-zodiac hereon) for both Senetosa and Ajaccio calibration sites. The main reason is that a waverider buoy can't be towed by a boat. As a consequence, handling (from sea to boat and vice versa) leads to losses of the GPS signal that affect the ambiguity resolution in the data processing. The use of the GPS-zodiac instead of the previous buoy avoids these problems and thus allowed us to record SSH continuously at 1Hz (Bonnefond et al. 2015).

At Senetosa, a weather station has been installed at the lighthouse since 2000, near the GPS reference point. The main goal of this station is to provide atmospheric pressure to correct the tide gauge measurements and to derive the dry component of the tropospheric correction. Atmospheric pressures from Ajaccio (~40 km North) and Figari (40 km East) provided by Météo-France are also used as back up in case of local station outages.

7.1.1.2.4 Pre-launch Site Characterization

Synopsis of the pre-launch activities:

- geoid extension using the CalNaGeo system (Figure 21) at dedicated location under the SWOT swath (and/or nadir). The already planned geoid extension in the frame of Sentinel-3 mission needs very few changes to be adapted to SWOT if the nominal orbit is phased as illustrated in Figure 25 (right)
- feasibility study to install new sensors (tide gauge, GPS, …) on the "Boussole" buoy (Figure 25 left)
- regular deployment of the CalNaGeo at the previous mapped locations to derive the differences in term of oceanic signal compared to coastal tide gauges measurements. These measurements will be used as constraints for the development of a specific ocean dynamics model with high space and time resolutions.
- adaptation of the regional calibration method to SWOT
- use of the simulator to generate SWOT measurement and derive simulated SSH biases:
    - from direct and indirect methods
    - from the regional calibration method

7.1.1.2.5 Post-launch Cal/Val Activities

Synopsis of the post-launch activities:

- regular deployement of the CalNaGeo at the previous mapped locations at the time of SWOT overflights
- use of the "Boussole" measurements (sea level) in the calibration process (direct method)
- derive SSH biases time series using:
    - direct and indirect methods
    - regional calibration method
- compare radiometer wet tropospheric path delays to those derived from GPS measurements.

7.1.1.3 Bass Strait Cal/Val Site

7.1.1.3.1 Site Description

The Bass Strait calibration and validation site has been used in the derivation of absolute bias estimates for the Jason-class satellite altimeters since the launch of the TOPEX/Poseidon mission in 1992. The site is one of three primary validation facilities contributing to the Ocean Surface Topography Science Team, and the sole site located in the Southern hemisphere. The historical comparison point is located off the north west coast of Tasmania, Australia (40° 39'S, 145° 36' E, Figure 26), and is now permanently instrumented with a suite of moored oceanographic instruments. The moored ocean sensors enable the production of a precise time series of sea surface height, with an absolute datum imposed through episodic deployments of GPS equipped buoys. Additional data is obtained from the land based GPS and tide gauge located in Burnie (Figure 32). This historical comparison site, together with comparison points (CPs) for Sentinel 3A and 3B (see later) are shown in Figure 32– also shown is the nominal 21 day SWOT orbit.

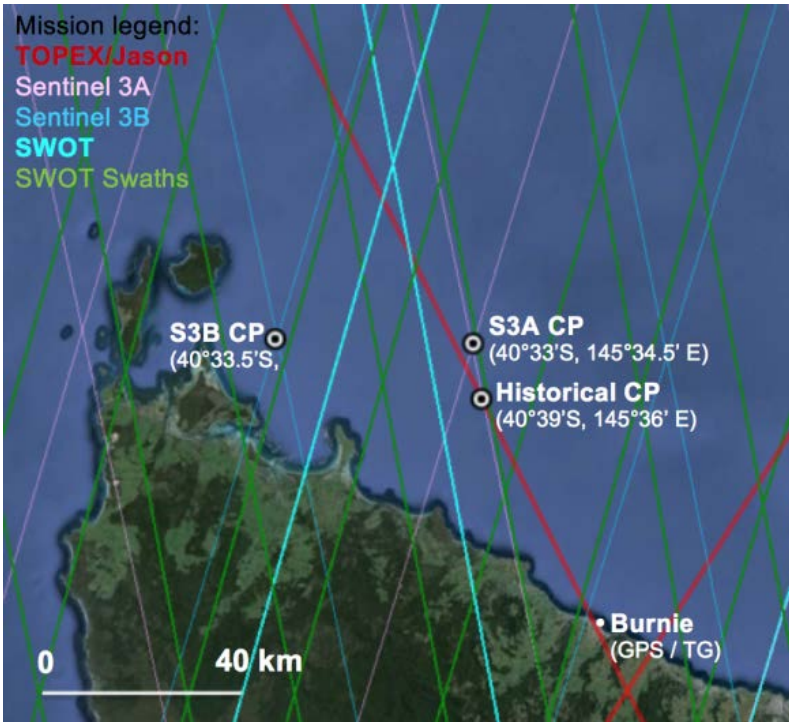


Figure 32. The Bass Strait Cal/Val facility with Jason-series "historical" comparison point (CP), Sentinel-3A and 3B CPs. SWOT 21d orbit is shown in cyan, with inner (10 km) and outer swath in green. SWOT orbit from SWOT_Science_Option4_ScienceP59_over_CalValP3_Swath_10_60.

In 2015, the Bass Strait facility will be augmented with a second comparison point to facilitate validation of the Sentinel-3A altimeter (S3A CP, 40° 33'S, 145° 34.5'E, Figure 32). Pending ongoing support from Australian funding agencies, we plan to deploy a third comparison point to the West of the primary comparison point to enable validation of the Sentinel-3B mission (S3B CP, 40° 33.5'S, 145° 06'E, Figure 32). This location is positioned close to the Hunter group of Islands in Bass Strait, providing a validation target that is closer to the coast (~12 km) and in a region of more complex ocean dynamics compared with the primary Jason-class comparison point. Together, these sites located in the south east corner of Bass Strait, augmented with high resolution modeling will provide the basis for the Australian contribution to absolute validation for the SWOT mission.

The 21 day orbit for SWOT has the following characteristics with respect to the historical, S3A and S3B CPs (refer Figure 32):

- SWOT nadir crossover is ~50 km to the north of historical CP (difficult to instrument given sea floor sediment at this location).
- The historical and S3A CPs just within inner swath of Desc Pass 65 (9 km from nadir track). GPS buoys could be used to observe SSH slope, and high resolution models used for differences in tide. These CPs would also be suitable for KaRIN of Pass 328 (Asc).
- The S3B CP is just outside inner swath of Pass 328 (Asc) but suitable for KaRIN of Pass 328 (Asc) and Pass 65 (Desc).

The nominal 1 day orbit for SWOT (Figure 33) is nadir ~35 km to the east of the historical CP. Site suitable for KaRIN only.

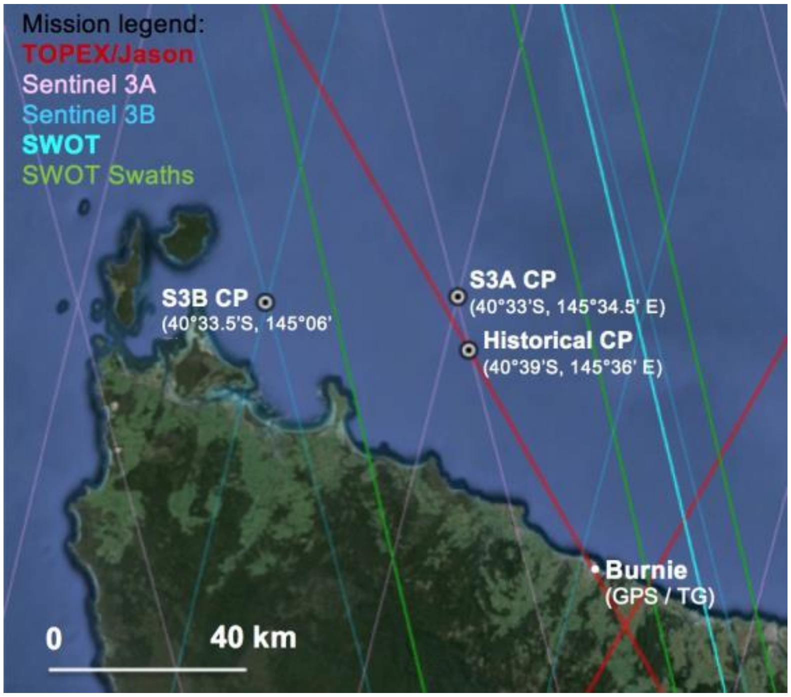


Figure 33. As per Figure 26 but showing the SWOT 1 day orbit from SWOT_Science_Option4_ScienceP59_over_CalValP3_Swath_10_60.

7.1.1.3.2 Site Goals

The primary goal of the Bass Strait validation site is to provide cycle-by-cycle absolute bias estimation for the SWOT mission. Our contributions will be centered on the locations designated by the historical (40° 39'S, 145° 36' E) and S3B (40° 33.5'S, 145° 06'E) comparison points (see Figure 32). High spatial and temporal resolution ocean modeling will augment in situ data that will include various point based absolute sea level and surface topography measurements, and network based estimates of integrated total zenith delay from the troposphere. We await decision on the final SWOT ground track to fully determine our experiment design.

7.1.1.3.3 Site Instrumentation

The primary instrumentation will include moored oceanographic sensors at the two comparison points. The moored arrays provide precise sea surface height on a 5-minute time base derived from bottom pressure and integrated temperature and salinity observations through the water column. We will investigate the acquisition of wave data from upward looking moored sensors, or surface based wave buoys. Currents will also be observed through the water column. The absolute datum of the sea level data will be derived using episodic GPS buoy deployments, with processing against land based GPS reference stations. The S3B comparison point at 40° 33.5'S, 145° 06'E (Figure 32) is closer to the coast and near the Hunter Island group in Bass Strait. This will enable the collection of a dense network of integrated water vapour measurements from GPS stations to be deployed in the area. To facilitate high resolution ocean modeling, campaign based acquisition of sea surface height data from autonomous vehicles will be investigated (pending Australian resources), in addition to acquisition of supplementary bathymetry data to aid model development.

7.1.1.3.4 Pre-launch Site Characterization

The various comparison points will be well characterized prior to the launch of SWOT given their intended use for Jason-3, Sentinel-3A and Senitnel-3B. Aspects of this characterization will include model development and validation that will enable improved ability to resolve processes within the SWOT swath.

7.1.1.3.5 Post-launch Cal/Val Activities

Post-launch activities will include ongoing mooring and buoy data collection. Resourcing will likely dictate data will be downloaded from the moorings every six months, with this to be optimized around the time of launch of SWOT. High resolution ocean modeling will be undertaken on a regular time step using a domain spanning Bass Strait, nested in a larger model. GPS data will be downloaded remotely enabling regular production of zenith wet delays. Dedicated campaigns for profiling surface topography will be undertaken at set epochs, dependent on available resources. A secondary activity will be comparison of SWOT data against the global tide gauge network in order to assess the ability of SWOT to assess accurate changes in regional mean sea level.

7.1.2 Validation of relative 2D SSH and currents

The Cal/Val sites described in this section aim at validating the relative 2D SSH and its derivatives (e.g. geostrophic currents), often combining existing infrastructures (e.g. HF radars, ship and ADCP current data and glider data) and new measurement techniques such as lidar and/or in situ instrumentation. These local validation sites are complementary with global metrics (e.g. statistical or global in-situ networks). Having at least two or three validation sites makes it possible for local/global comparisons to infer the influence of any error that depends on in-orbit and geophysics conditions (e.g. geoid, tides, corruption by coastal layover). To that extent, the ocean calibration sites described in this document provide a range of ocean dynamics, tides, bathymetry, wind and sea state conditions.

In addition to their particular dynamics, all of the validation sites will:

- evaluate the evolution of the dynamics (feature & front detection, 2D spectra) over the fast-repeat mission phase using SWOT and multi-satellite analysis, and available airborne and in-situ surface observations
- evaluate the associated vertical structure of the SWOT SSH, in comparison with available in-situ data and HR models
- validate 2D SSH reconstruction techniques for gridded fields based on SWOT & available nadir altimeter data during the fast sampling phase and the nominal phase

7.1.2.1 Gulf Stream Validation Site (Backup US Project Site)

7.1.2.1.1 Site Description

The Gulf Stream Cal/Val site is located off Cape Hatteras in North Carolina off the US east coast (see Figure 34). It is centered on the crossover point of the 1-day repeat orbit.

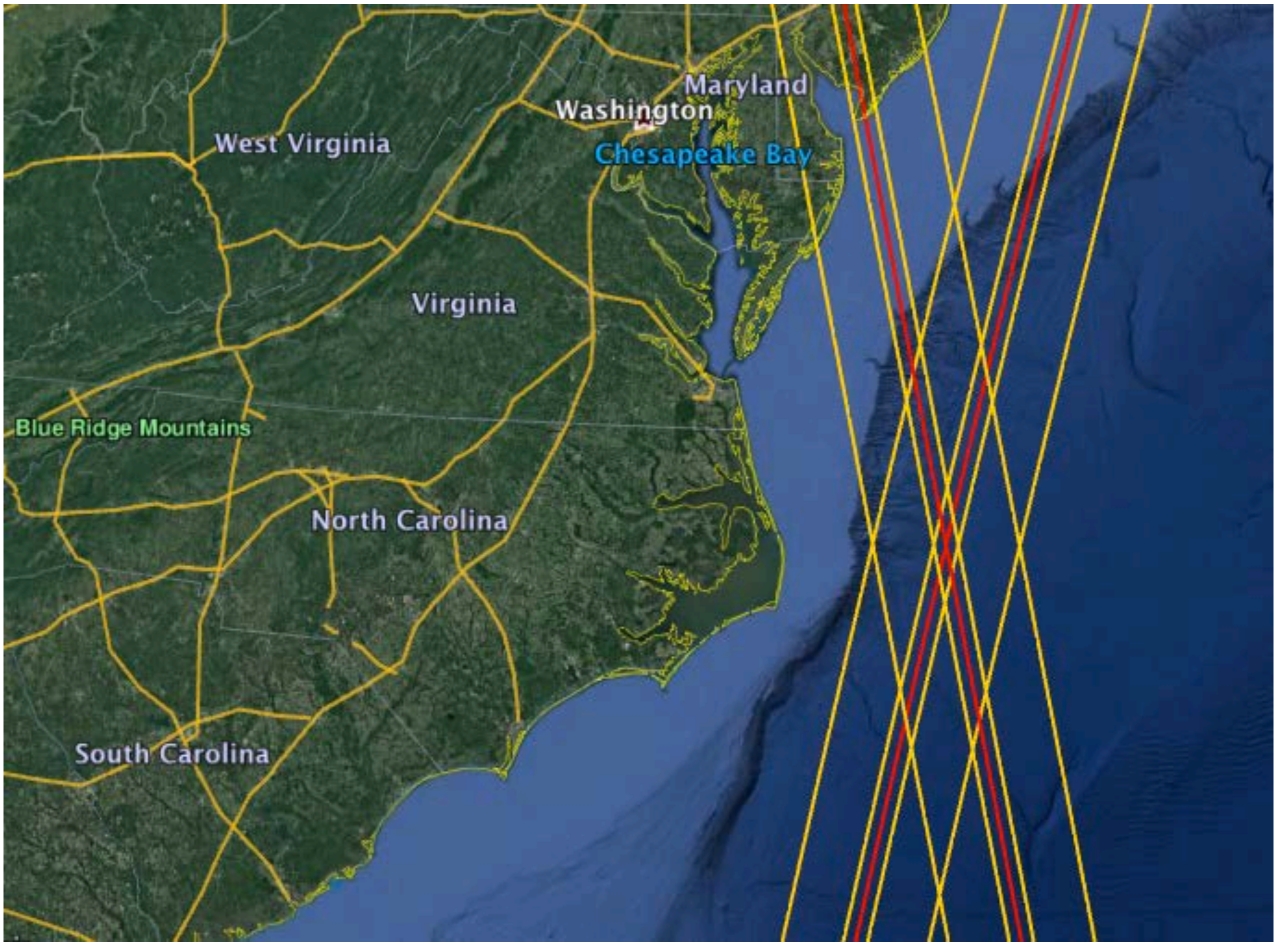


Figure 34. Tracks of the 1-day repeat phase of SWOT, with a crossover point off Cape Hatteras in North Carolina of the US east coast.

The Gulf Stream site is selected as the backup US project site because of the following considerations:

1) The Gulf Stream is the strongest western boundary current. It is typically 100 kilometres wide and can be traced down to at least 1000 m. The current velocity is fastest near the surface, with the maximum speed over 2 m/s. Beginning in the Caribbean and ending in the northern North Atlantic, the Gulf Stream System plays an important role in the poleward transfer of heat and salt and serves to warm the European subcontinent. The Gulf Stream system is among, if not, the most studied oceanographic feature. In addition to the strong current, the Gulf Stream is associated with high degree of mesoscale and submesoscale activities. As a result, the Gulf Stream system and its mesoscale and submesoscale variability have been the focus for numerous observational, modelling and theoretical studies (e.g., the recent LATMIX seasonal submesoscale experiment). In addition to major field programs, the Gulf Stream was also seen as the first oceanographic feature by the earliest altimetry satellites (e.g., Seasat, Geosat).
2) In the deep ocean region of the SWOT crossover, the Gulf Stream current is strong and so this site is not well suited to maintaining station-keeping gliders or repeat glider lines, or stable mooring lines. As such, it has not been proposed as the primary US project site

3) Another consideration for the Gulf Stream site as a US project site is simply because of its proximity to the coast so as to support both airborne flights and deployment/recovery of in situ sensors/platforms including ships and autonomous vehicles. However, the strong currents may make operation of some such assets infeasible.
4) Although the Fast-sampling Phase crossover position is in the highly energetic deep basin, which is challenging for maintaining an extensive array of in-situ observations, the 1-day swath extends towards the coast over the wide shelf of the Mid-Atlantic Bight. This shelf region is already well-sampled with the MARACOOS coastal observing system, allowing good external in-situ validation of the SWOT SSH and geostrophic currents. This inshore site will provide a second backup site for the US CalVal activities.

7.1.2.1.2 Site Goals

Starting with the SWOT Fast-sampling phase, the goals for this site are:

- To validate the SWOT SSH observations and swath averaged spectra from 15 to 150 km for this mid-latitude western boundary site with high mesoscale and sub-mesoscale dynamics and moderate tides and in the well-sampled Mid-Atlantic Bight region **using whatever data are available given that this is not a primary site.**
- evaluate the surface wave conditions for this particular site with moderate swell, and the impact on the sea state bias estimation
- evaluate the SWOT signal to noise for the particular dynamics at this site (eg, strong submesoscale signal in winter, higher SWH in winter, the opposite in summer conditions)

7.1.2.1.3 Site Instrumentation

The Gulf Stream system is routinely monitored by the Mid-Atlantic Regional Association Coastal Ocean Observing System (MARACOOS), a regional association of the national Integrated Ocean Observing System (http://maracoos.org/). MARACOOS maintains a number of observational assets including: coastal weather network, primary and back-up satellite data acquisition centers, a triple-nested multistatic HF Radar network, an accelerating autonomous underwater glider capability, and mission-specific statistical and dynamical ocean forecast models.

In the coming years leading to the launch of the SWOT, *MARCOOS will surely maintain these existing observing systems*. More importantly, MARACOOS will introduce new technology as they become available in the future. MARACOOS is currently focusing on the development and deployment of a fleet of gliders to continuously patrol the coastal oceans. In order to achieve this goal, we are employing some of the same “smart” technologies that NASA has used in deploying earth-orbiting satellite constellations. This technology allows the gliders to adjust their current course based on the previously collected physical and optical data. When realized, this will allow for 24-hour-a-day data collection without constant supervision by a human scientist. The end result will be a glider fleet that will be able to detect and track oceanic features (i.e.: upwelling events, red-tides, and coastal eddies) from their formation to dissipation, improving our current understanding of the dynamical nature of coastal ecosystems and providing earlier detection of oceanic features that develop offshore and are advected into coastal waters.

7.1.2.1.4 Pre-launch Site Characterization

The Gulf Stream system has already been studied extensively. No additional SWOT-dedicated characterization is needed at this site before launch.

7.1.2.1.5 Post-launch Cal/Val Activities

If the primary Cal/Val site of the US west coast is found not to be viable for some reason, some or all of the planned Cal/Val activities for the primary site can be moved to the backup site. This is a contingency scenario that will be defined when/if it becomes necessary.

7.1.2.2 California Current/Coast Cal/Val Site (Primary US Project Site)

7.1.2.2.1 Site Description

The California Current Cal/Val site is located off the coast of central California in the eastern North Pacific Ocean (see Figure 35). It is centered on the crossover point of the 1-day repeat phase of SWOT. There is also extensive instrumentation over the portion of the 1-day swath that extends toward the California coast, which can be considered to be part of the Cal/Val site.

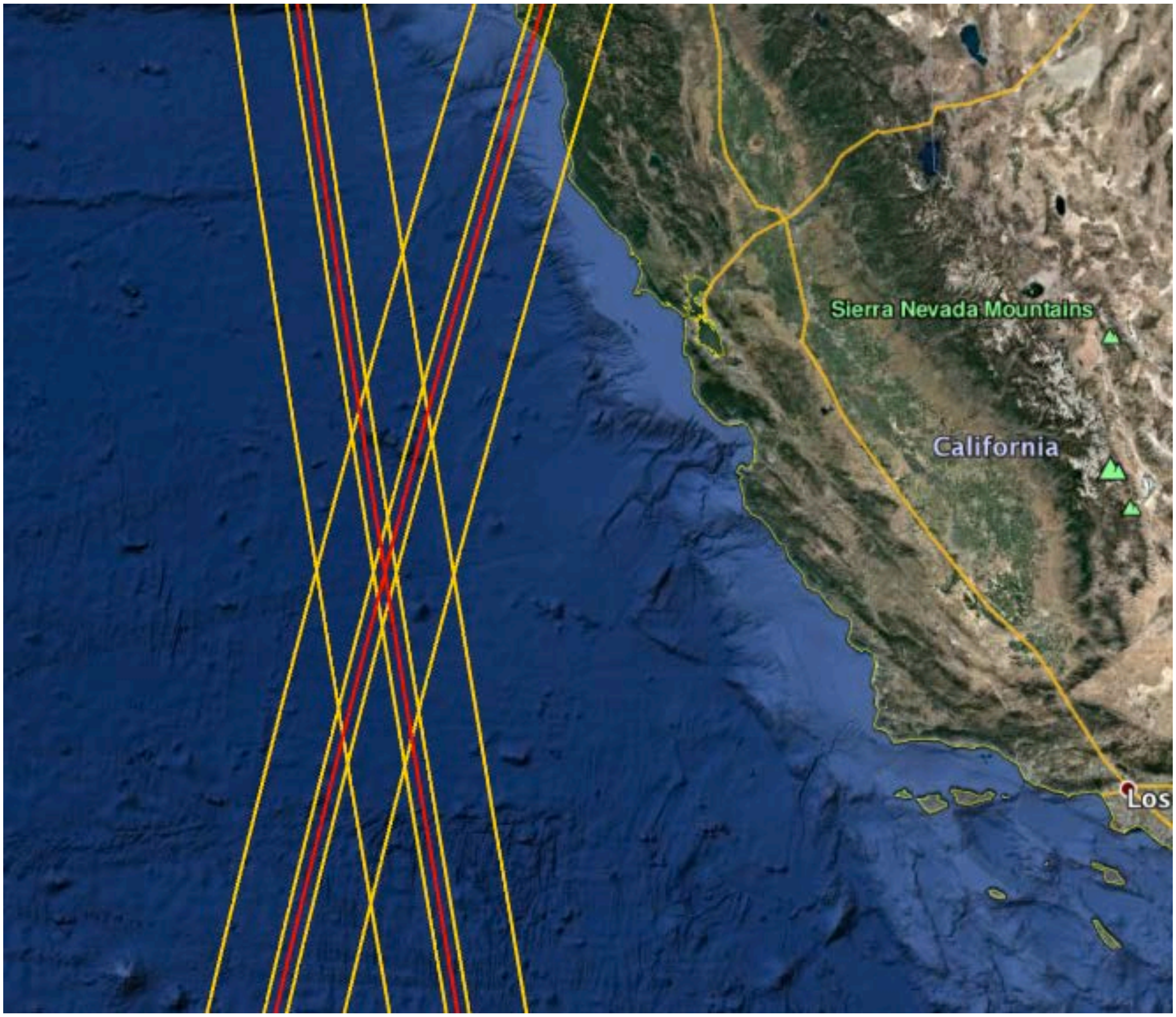


Figure 35. Tracks of the 1-day repeat phase with a crossover point off the central California coast

The California Current is an Eastern boundary current and is also part of the North Pacific Gyre, a large swirling current that occupies the northern basin of the Pacific. The California Current System is associated with major upwelling zones to support a very productive ecosystem and therefore fishery. It is part of a Pacific Ocean current that moves southward along the western coast of North America, beginning off southern British Columbia and ending off southern Baja California. The movement of northern waters southward makes the coastal waters cooler than the coastal areas of comparable latitude on the east coast of the United States (e.g., Gulf Stream). Additionally, extensive upwelling of colder sub-surface waters occurs, caused by the prevailing northwesterly winds acting through the Ekman Effect. The winds drive surface water to the right of the wind flow, that is offshore, which draws water up from below to replace it. The upwelling further cools the already cool California Current. This is the mechanism that produces California's characteristic coastal fog.

The California Current region was the location of AirSWOT and MASS ocean flights as well as UCTD data collection during April 2015. This campaign encountered many weather-related and logistical challenges. Since that time, the SWOT fast-repeat orbit has been changed so that the crossover point off the US west coast has been shifted further to the west, out of US Navy warning zones, but the additional distance from shore presents further challenges for ships and aircraft.

The typical current at the California site is benign enough for gliders to maintain station, however, so the California site has been selected as the primary US project ocean Cal/Val site.

7.1.2.2.2 Site Goals

The goal for the California site is to carry out the SWOT ocean cal/val at short wavelengths. There will also be opportunities for many local field campaigns that can be coordinated in order to learn the SWOT calibration parameters.
Starting with the SWOT Fast-sampling phase, the main goals for this site are:

- To validate the SWOT SSH observations and swath averaged spectra from 15 to 150 km for this eastern boundary site with moderate tides, and moderate mesoscale and sub-mesoscale dynamics
- evaluate the surface wave conditions for this particular site with large swell developed over the entire Pacific Ocean, and the impact on the sea state bias estimation
- evaluate the SWOT signal to noise for the particular dynamics at this site

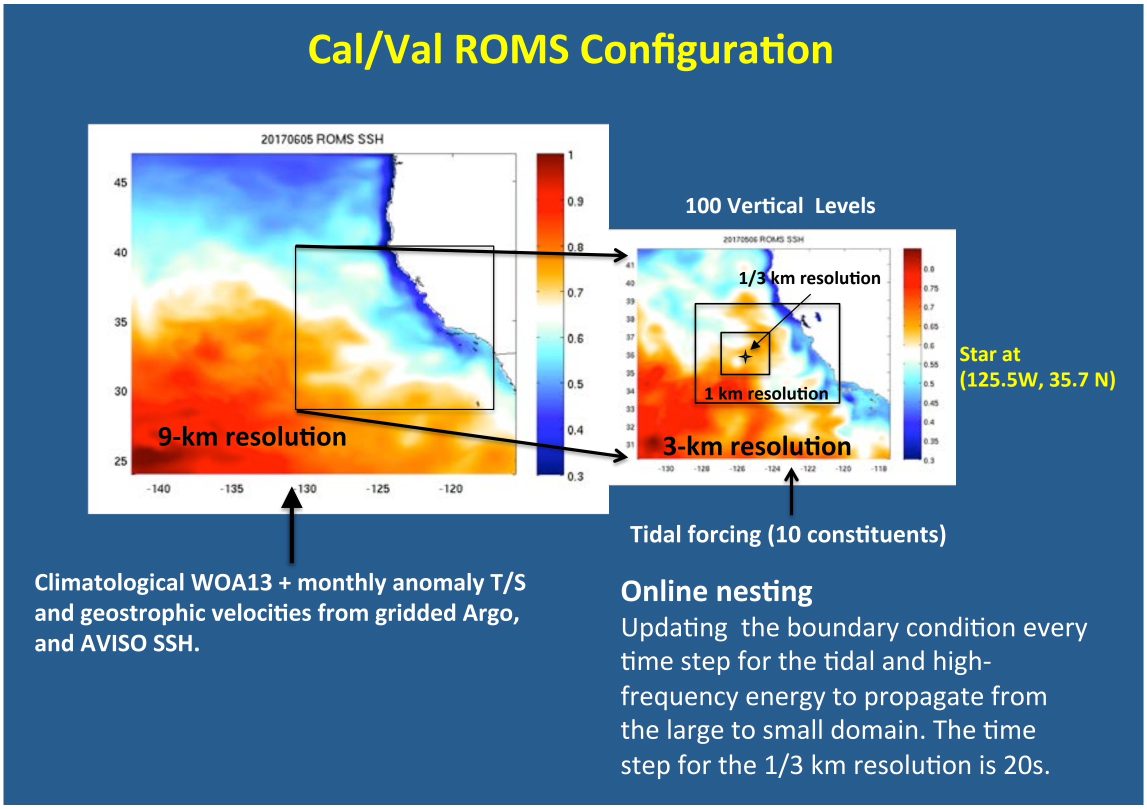
7.1.2.2.3 Site Instrumentation

The California Cal/Val site is the baseline location for the glider array described in Sect. 6.4.

Currently, a number of data sets are being collected in real-time by the Central and Northern California Ocean Observing System (CeNCOOS) and Southern California Coastal Ocean Observing System (SCCOOS) funded by NOAA Integrated Ocean Observing System (IOOS). The Monterey Bay Aquarium Research Institute (MBARI) also has a more than 30 years history to measure the Monterey Bay and its nearby central California coastal ocean.

Specially, the surface current is measured by a network of high-frequency (HF) radars along the California coast at hourly interval and a spatial resolution of 1 km. A mooring (known as M1) at the center of the Monterey Bay is collecting a continuous time series of temperature and salinity at all depths. Vertical profiles of temperature and salinity along three Spray gliders continuously in time. MBARI frequently deploys their autonomous underwater vehicles (AUVs) to measure vertical profiles of temperature and salinity at higher spatial resolution.

A dedicated effort of developing a nested system of ocean general circulation models has been put in place to support the SWOT ocean science validation at the California site. The model configuration is shown in Figure 36. The model will assimilate data from the in-situ ocean observing system (glider array as the baseline) plus other routinely available in-situ and satellite observations to produce nowcast and forecast to support the SWOT ocean validation activities. This effort is aimed to produce optimal estimates of the state of the ocean for comparison to SWOT observations for validation and understanding. The data from the MASS lidar system would also possibly be incorporated by the system for supporting CalVal.



Cal/Val ROMS Configuration

Climatological WOA13 + monthly anomaly T/S and geostrophic velocities from gridded Argo, and AVISO SSH.

Online nesting

Updating the boundary condition every time step for the tidal and high-frequency energy to propagate from the large to small domain. The time step for the 1/3 km resolution is 20s.

Figure 36. Configuration of assimilative model at the California Cal/Val site.

7.1.2.2.4 Pre-launch Site Characterization

The California Cal/Val crossover site is the location for the pre-launch glider experiment described in Sect. 6.4.

The pre-launch characterization of the California Current site began in April 2015 with in situ measurements coincident to AirSWOT and MASS overflights. During the 2015 data collection, problems were found with the site accessibility due to Navy airspace restrictions, so the site has been shifted slightly to the west to avoid these restrictions during the post-launch calibration phase.

During the 2015 campaign, three types of instruments were deployed over a period of two weeks. An underway CTD sensor was deployed from a ship going at about 10 kt. The UCTD measured vertical profiles of temperature and salinity down to about 200 meters along the ship route. Three EM-APEX floats were deployed to measure not only vertical profiles of temperature and salinity as the conventional Argo floats but vertical profiles of velocity as well. Multiple surface drifters were also deployed to measure the surface current that was used to validate the HF radar derived surface current and quantify the effect of surface current on AirSWOT measurements. A real-time 3D data assimilative ocean general circulation model was also used to facilitate the planning of in situ field campaigns as well as data interpretation and validation.

7.1.2.2.5 Post-launch Cal/Val Activities

During the post-launch calibration phase, Cal/Val activities at the primary California ocean Cal/Val site will include the MASS and/or in situ glider campaigns. See Sects. 2.3.2 and 6.4 for details on these activities.

7.1.2.3 Mediterranean Validation Site (French Project Site)

7.1.2.3.1 Site Description

The western Mediterranean site is chosen as a mid-latitude site with **moderate eddy energy levels & weak tides**. The Fast Sampling Phase of SWOT will allow validation of the 15-150 km ocean processes at two sites here (Figure 37). Compared to regions in the Atlantic or Pacific basins situated at the same latitudes, the **Mediterranean Sea dynamics are energetic at short scales** (the Rossby radius is about 10-15 km; feature scales of 30 km). These small dynamics are partly captured by alongtrack altimetry but not well by today's mapped data. These small dynamics are dominated by geostrophic motions (> 90% in the energetic currents). Being an enclosed sea, the Mediterranean basin has a small horizontal extent but relatively strong winds, generating **short rapid sea state conditions rather than long regular swell**, different from other ocean validation sites in the Atlantic or the Pacific. Two experimental sites are planned – one at the 1-day repeat crossover points between the Baleares Islands and Algeria, the other offshore from Toulon on the French coast.

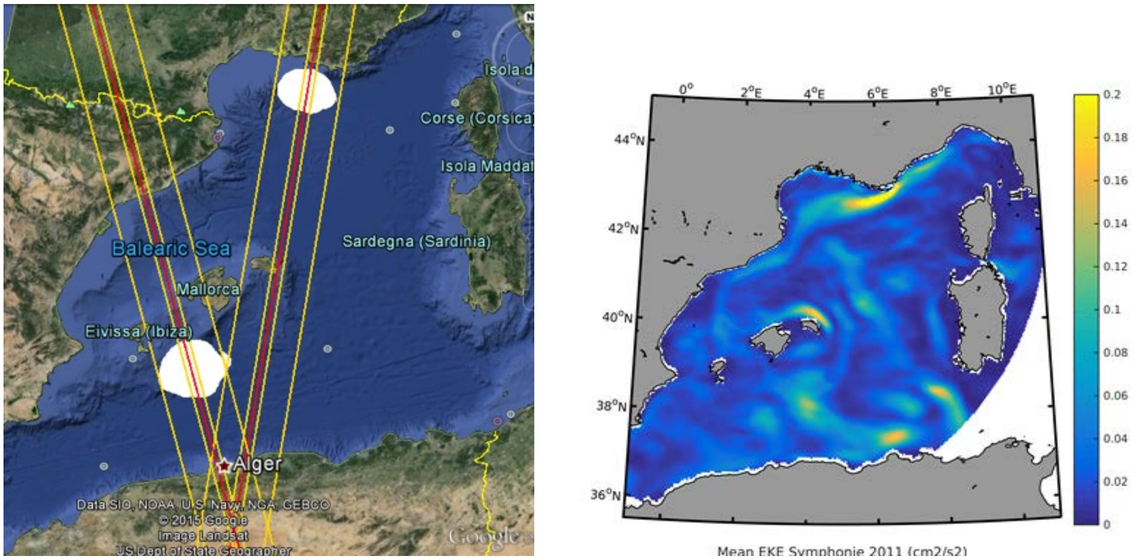


Figure 37. Left: Tracks of the 1-day repeat phase of SWOT, with a crossover between the Balearic Islands and Algeria. The red dashed circle shows the proposed validation region near the SWOT 1-day crossover, and the pink dashed curve the validation region in the Ligura-Provencal Current. Right: Mean eddy kinetic energy (cm^2/s^2) based on 1 km Symphonie model results in the NW Mediterranean Sea. Due to the dominance of small-scale structures most of the energy is at short scales of 20-30 km

7.1.2.3.2 Site Goals

During the SWOT Fast-sampling phase, the goals are to:

- validate the SWOT SSH observations for this particular site with weak tides, moderate eddy energy and dominant small-scale dynamics
- evaluate the surface wave conditions for this particular site with low swell, and dominant short sea-state, and its the impact on the SWOT SSH estimation
- evaluate the SWOT signal to noise for the particular dynamics at this site

7.1.2.3.3 Site Instrumentation

The aim is to deploy a **self contained, rapidly deployed and low cost experimental setup** aimed at quantifying the two-dimensional SSH structures at scales from a few to tens of km, as well as their associated phytoplankton community structures.

The planned instrumentation includes pairs or a **batch of three gliders** that will perform a formation flight within the SWOT swath. Gliders should be available from the Spanish IMEDEA/SOCIB group (southern site) and French MOOSE observations (northern site). The gliders will be fitted with CTD and a suite of optical sensors (fluoresence and backscatter in several wavelengths). The gliders will make shallow dives (to 100 m depth), remaining at a fixed distance one from another (about 1 km apart). Each of them will monitor the surface current during the time spent drifting at the surface between two successive dives. We will have access to the surface velocity gradient tensor at kilometric scale, along the gliders path. This in situ dataset will allow assessing quantitatively the capability of SWOT to capture the surface current (dominated by geostrophy), but also key dynamical quantities derived from it (vorticity, divergence and strain rate).

The plan is also to **map the physical and biological parameters** including the phytoplankton community with an underway instrument and a towed vehicule, operating around the glider fleet. The small ship-based instrumentation should include a **Moving Vessel Profiler 200 (MVP), a bench flow cytometer CytoSense** connected to the ship surface pumping system, and an **echosounder.** The MVP is an automatic winch system that is used to deploy a freefall “fish” which contains the various instruments (CTD, LOPC and fluorometer). The “fish” is towed behind the moving ship performing high-frequency free-falling profiles from the surface to a given depth. The MVP allows repeated synoptic sections of fast-evolving submesoscale structures. The observations can be used to reconstruct the vertical distribution of both physical and biological parameters within the water column.

Only half the crossover is over the ocean, and a large part of this is within the Algerian EEZ waters which can be difficult to access for airborne or in-situ deployments. The priority is therefore to instrument the 1-day swath that extends back towards the Balearic Islands, in a region of moderate eddy energy. This site is easily reached by airborne instruments, including the possibility to use a French airborne Lidar system with mutli-spectral camera to better situate the position of the surface fronts.

The two proposed sites will be used for a detailed cross-validation of SSH from SWOT and available nadir altimeters. The **deployment of GPS buoys** is possible for the Fast sampling phase at one site. **HR realistic models** (1 km resolution) are available in NRT for SSH and waves. **Waverider buoys**, adapted to measure the predominant short waves, will be tested. **HF Radar** is available near Toulon providing surface currents in the 150 km coastal band for the northern site.

The vicinity of the proposed experimental areas to our logistical sites (France mainland and Balearic Islands) makes this region a good benchmark for our project. Aside from the logistics issues, the diplomatic aspects (EEZ clearances and related issues) have also been proven to be tractable, with currently ongoing glider transects off Algiers as part of the SOMBA project led by LOCEAN.

7.1.2.3.4 Pre-launch Site Characterization

Pre-launch campaigns have started and others are planned at both sites in the next years, in order to practice the experimental deployment and fine-tuning submesoscale resolving adaptive sampling techniques. Figure 38 displays the legs of the OSCAHR campaign (Gulf of Lion, October 2015, PI: A. Doglioli) where quasi-synoptic, high resolution CTD casts have been recorded by a towed vehicle along one Jason-2 and two SARAL/Altika tracks with the aim of comparing altimetry-derived and in situ estimations of sea level anomalies, together with the deployment of surface drifters, glider operations, and HF radar observations. HR realistic models (1 km resolution) are available for SSH and wave analysis pre-launch. Waverider buoys, adapted to measure the predominant short waves, will also be tested prelaunch. HF Radar is available near Toulon providing surface currents in the 50 km coastal band for the northern site. Joint analysis of collocated SAR nadir altimetry, gliders, and HF radar are underway and will continue at both sites to characterize the observed dynamics.

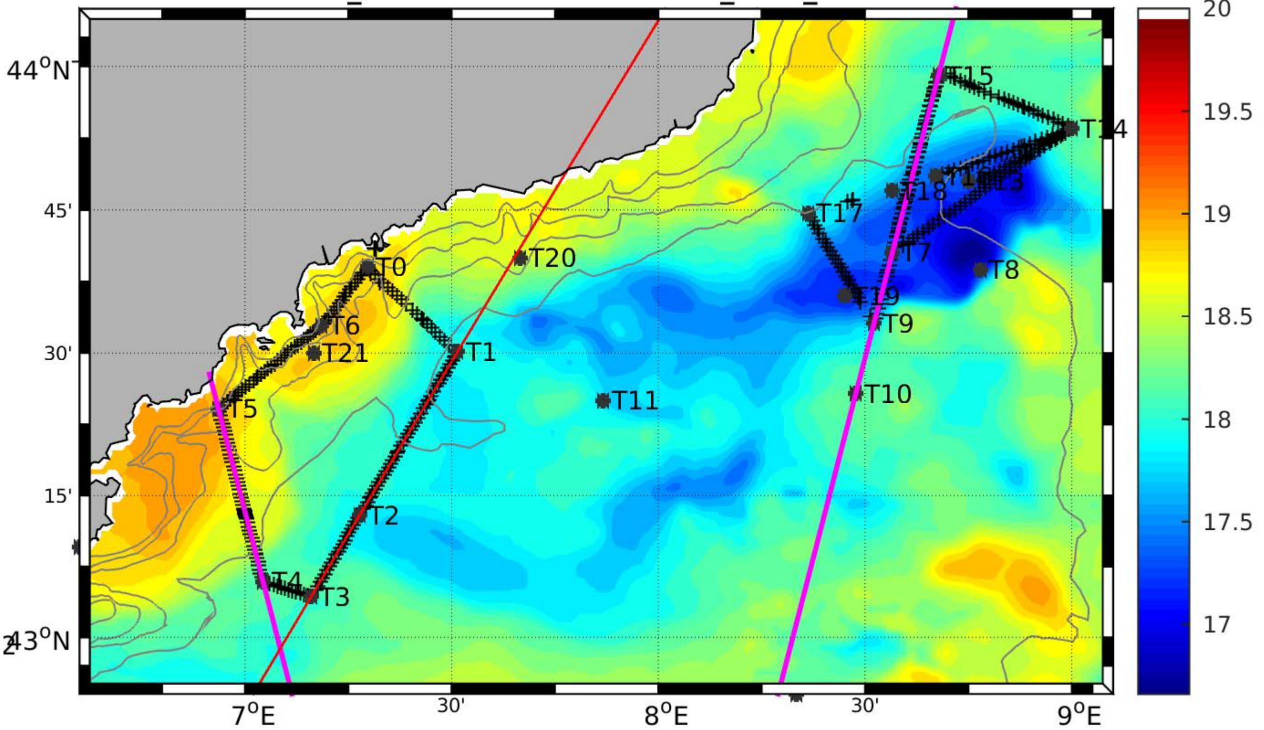


Figure 38. Legs of the OSCAHR campaign (black crosses) and tracks of Jason-2 and SARAL/Altika (resp. red and magenta lines). The background color represents GHRSST L4 Sea Surface Temperature. The campaign (PI: A. Doglioli) took place in October/November 2015. Among other objectives, the campaign aimed at testing SLA reconstruction from quasi-synoptic CTD casts made with a towed vehicle and supported by current and hydrographic observations from surface drifters, HF radar, and one glider.

A HR geoid is available from the French Marine service (SHOM) in the NW Mediterranean. A HR mean sea surface (MSS) can be developed in each region, using the HR geoid, new satellite altimetry and gravity mission data, and in-situ observations including towed GPS observations.

7.1.2.3.5 Post-launch Cal/Val Activities

Post-launch validation will concentrate on the self contained, rapidly deployed and low cost experimental setup at both the northern and southern sites **during the fast sampling phase,** as described in section 8.1.2.2.3 and 8.1.2.2.4.

7.1.2.4 Loyalty Site

This site has been proposed as an opportunity site to the ongoing ROSES/TOSCA in case the 1-day orbit is confirmed to pass over the Loyalty Basin. It is associated to the proposal entitled “SWOT in the Tropics, A Case Study In South West Pacific” lead by L. Gourdeau. In the case that the fast sampling orbit finally selected by the ST does not pass anymore in the Loyalty basin, this site would not be included anymore in the list of potential Cal/Val sites.

7.1.2.4.1 Site Description

The Loyalty basin is situated in South West Pacific. It is enclosed by the Loyalty archipelago on the East and the Grand terre island, all forming the French Territory of New Caledonia (Figure 39). This basin has been studied by oceanographers for tens of years and with in-situ data collected during a dozen of cruises and consequently, the dynamics of the currents is particularly well known. It is a site selected in the AltiKa Scientific Team. Since the 90's, it has been fully mapped with multi-beam echo-sounders, its geological setting has been the subject of several publications, all making possible the computation of a high resolution geoid surface.

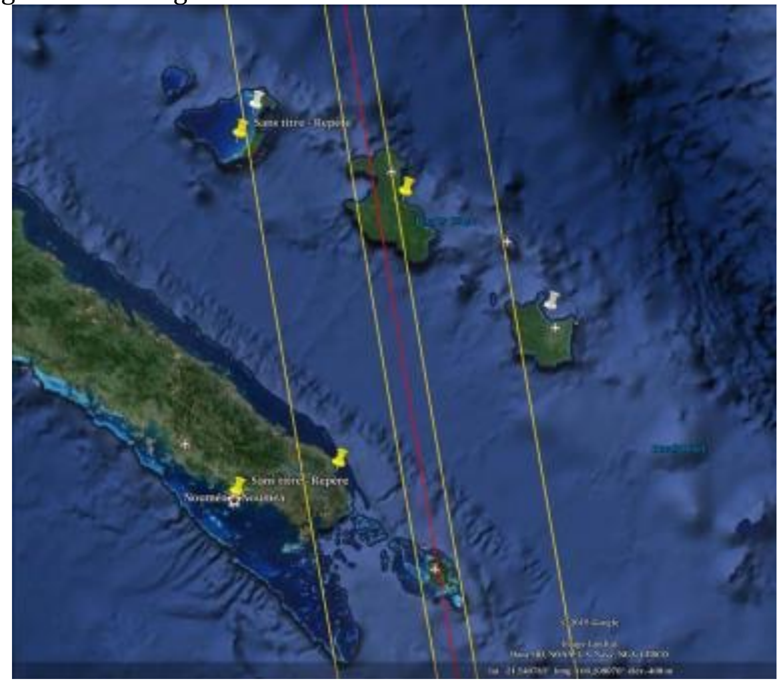


Figure 39. The yellow lines stands for the swath limits and the red line stands for the nadir track. The yellow pins give location of the existing tide gages when the white pins show the location of the planned ones.

7.1.2.4.2 Site Goals

This site will be dedicated to collecting sea surface height and dynamic height measurements in the along-track and cross-track directions, to provide surface wave data and mean sea surface height undulations. This site at 20°S is also a lower latitude CalVal site, impacted by tropical and subtropical dynamics.

7.1.2.4.3 Site Instrumentation

The archipelago is equipped with a dense GPS network, computed daily, and a network of tide gauges, geodetically linked to the GPS network. These in-situ permanent instruments give access to the instantaneous absolute sea-level at a few places within the SWOT swath.

The archipelago is equipped with a research vessel, N/O Alis, dedicated to works at sea in the vicinity of the islands. Together, the Territory owns a vessel that can be used for scientific work not exceeding a couple of days.

The archipelago is equipped with a network of meteo stations (at least one on each island, at the airport)

A wave radar is planned to be installed on one of the islands for studies of the wind induced sea surface roughness

7.1.2.4.4 Pre-launch Site Characterization

The operations that will be conducted before the launch are:

- Official sollicitations of both vessels for the fast sampling phase
- Sollicitations of the vessels for test cruises before the date of launch, in particular to test the use of CalNaGeo, the GPS floating sheet (Figure 13). The test cruises could be the opportunity to collect profiles of sea level anomalies along the nadir track of SWOT.
- Computation of a high resolution geoid model by combination of surface altimetry data, shipborne gravity data and geopotential inference from the submarine geological structure
- Install additional sensors (tide gauge, corner reflectors, submarine pressure gauges on reefs, etc …) according to ST recommendations and fundings.

7.1.2.5 Post-launch Cal/Val Activities

The post launch activities have to be considered for the 1-day - the fast sampling orbit.

During the fast sampling orbit, the vessels will be used to collect profiles of the absolute instantaneous sea surface height. The cruise plan will be elaborated following the recommendations of the ST (long along-track profiles vs cross-track from one outer rim of the swath to the other…).

7.2 Hydrology Cal/Val sites

7.2.1 River Cal/Val Sites

7.2.1.1 Willamette River Cal/Val Site (US Project Site)

7.2.1.1.1 Site Description

The Willamette River Cal/Val site is located in western Oregon, U.S.A., between the towns of Corvallis and Eugene (Figure 40). The river in this 75-km study reach is primarily gravel-bedded with a single-thread channel with occasional sections of multiple-thread channel, and relatively stable bed and banks. Though there are moderate-size flow regulation reservoirs in the upper watershed, the hydrograph of the river in the study reach is typical of temperate rain- and snow-fall river systems, with distinct and large regular peaks and recession limbs from October to June and a low flow period in the summer from July to September. This study reach has been the focus of previous SWOT-related studies, particularly the AirSWOT campaign in spring 2015. The Willamette River Cal/Val study site will be used validate SWOT's ability to detect water-surface elevation, slope, inundation extent, and discharge.

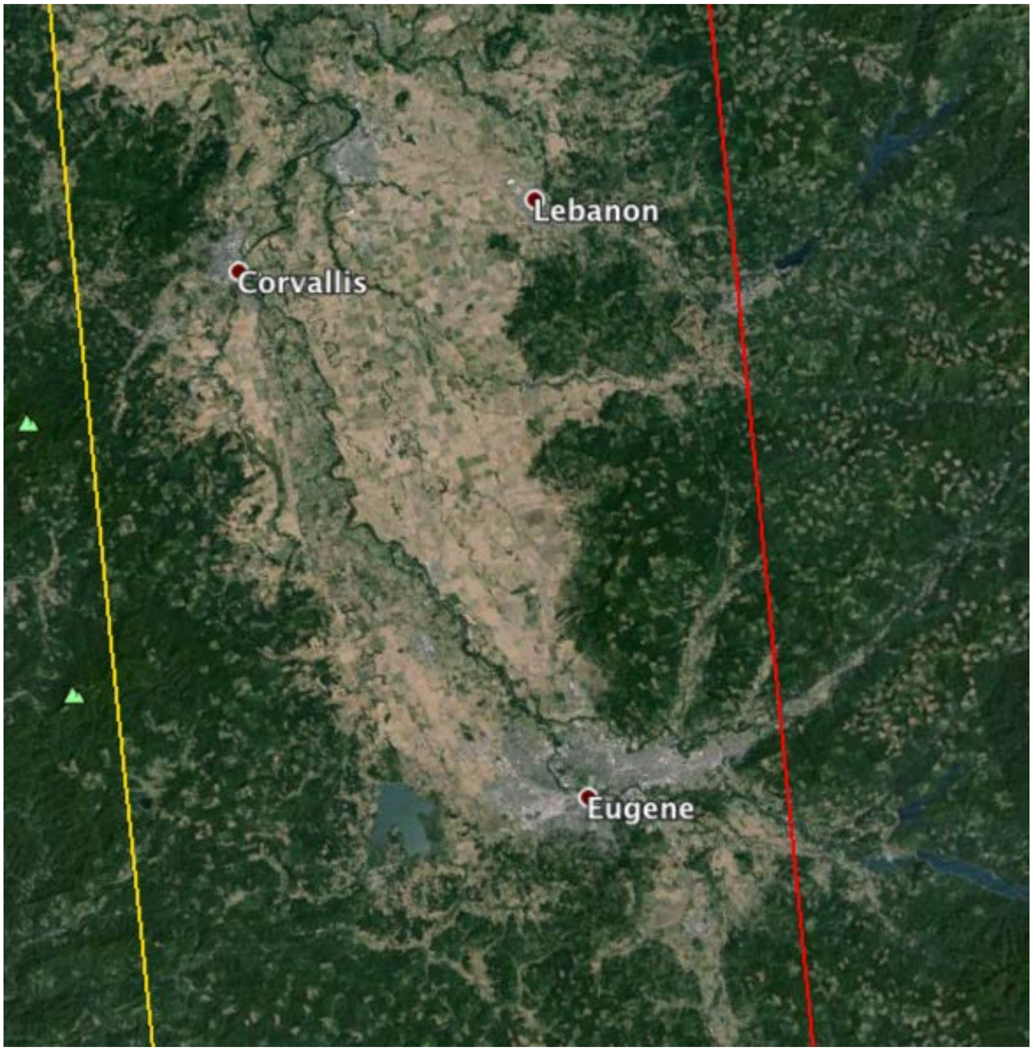


Figure 40. The Willamette River Field Site

7.2.1.1.2 Site Goals

There are two primary validation goal for the Willamette River Cal/Val site:

1. Validate SWOT's ability to measure and characterize rivers with single- and multiple-thread channels, typical of temperate climate rivers.
2. Characterize SWOT's ability to measure water-surface elevation, slope, inundation extent, and discharge in rivers near the 100 m baseline width requirement.

7.2.1.1.3 Site Instrumentation

There are three active discharge gages on the mainstem Willamette River in the study site, and one gage on each of the three major tributaries, making the study site relatively well-characterized for discharge. The overbank topography of the site was measured with aerial lidar in 2008-2009, though in some locations the river has changed substantially since that time. The bathymetry of the study reach has historical coarse bathymetry from widely-spaced (2+ km spacing) cross sections collected in 2002. More recently, new cross sections with approximately 2-km spacing and several long profiles have been measured as part of the AirSWOT campaign in spring 2015. Besides the gages already in operation on the river, there are no other permanent measurements being made.

One of the primary needs for the Willamette River Cal/Val site is a calibrated 1D or 2D hydraulic model to be able to test SWOT data products in both the pre- and post-launch periods. The 1D model may be developed in conjunction with the USGS following the AirSWOT 2015 campaign, however, it is not a funded project at present. The temporary deployment of pressure transducers along the long profile as well as boat-conducted surveys of water-surface elevation, such as utilized during the AirSWOT campaign in 2015, are suggested for instrumentation in the post-launch period.

7.2.1.1.4 Pre-launch Site Characterization

The pre-launch characterization of the Willamette River site began in spring 2015 with bathymetric, water-surface elevation and discharge measurements coincident to AirSWOT overflights. Field measurements were collected by USGS Oregon Water Science Center and University of Oregon (Mark Fonstad). Approximately six water-surface elevation long profiles and 20 cross sections were measured over a range of flows, though no data were collected during substantial overbank discharges. Discharge was measured at approximately 15 locations along the long profile during the flights and over a range of flows, as well as several smaller tributaries. In addition to the field data collection, the Willamette was flown six times by AirSWOT, including KaSPAR and near-infrared imagery, and these data will provide extensive additional information to help characterize the site and potential SWOT performance for water-surface elevations, slope, inundation extent, and discharge. The data processing for the AirSWOT data is ongoing and is expected to be completed by fall 2015.

Additional suggested pre-launch characterization activities for the Willamette River Cal/Val site will be the development of a 1D hydraulic model and potentially 2D hydraulic models in shorter subreaches. In addition, the 1-day fast repeat cycle may include the lower Willamette River (Corvallis to Portland) for which a sparse data collection effort might be warranted to characterize this part of the river.

7.2.1.1.5 Post-launch Cal/Val Activities

The Willamette River Cal/Val site is one of the only river sites that will be included in the 1-day fast repeat cycle immediately following launch. As such, during the 1-day fast repeat cycle the Willamette River Cal/Val site will be the focus of intensive measurements to help validate SWOT measurements of water-surface elevation, slope, inundation extent and discharge. Field measurements will be similar to the techniques utilized in the spring 2015 AirSWOT campaign, including boat-based measurements of water-surface elevation, slope, and discharge, as well as deployment of pressure transducers to measure temporal changes in water-surface elevation and slope. In addition to field measurements, the Willamette River Cal/Val site is a likely candidate for coincident underflights of AirSWOT, with measurements by KaSPAR and near-infrared camera to constrain water-surface elevation, slope, and inundation extent. Once developed, the 1D and/or 2D models will be used to diagnose and trouble-shoot any issues with the SWOT estimates for water-surface elevation, slope, inundation extent and discharge.

7.2.1.2 Garonne River Validation Site (French Project Site)

7.2.1.2.1 Site Description

The Garonne River (South West of France) is the 4th longest river in the country with a 55 930 km^2 drainage area. Two specific Garonne reaches are proposed as validation sites (Figure 41). For each reach, there are three operational water level gages (with rating curve), multiple bathymetry cross-sections and 1D/2D hydraulic models already implemented. The two reaches will be fully covered by the 1 day orbit (Figure 42). The upstream reach between Blagnac and Malause is 80 km long with a mean river width ~150 m (lower during the low flow season with sand bars) and river bathymetry slope around 0.9m/1000m. The downstream reach between Tonneins and La Réole is 50 km long with a mean river width ~180 m (also with sand bars during the low flow period) and a river slope around 0.3m/1000m.

Figure 41. Garonne River watershed and validation sites (in light blue)

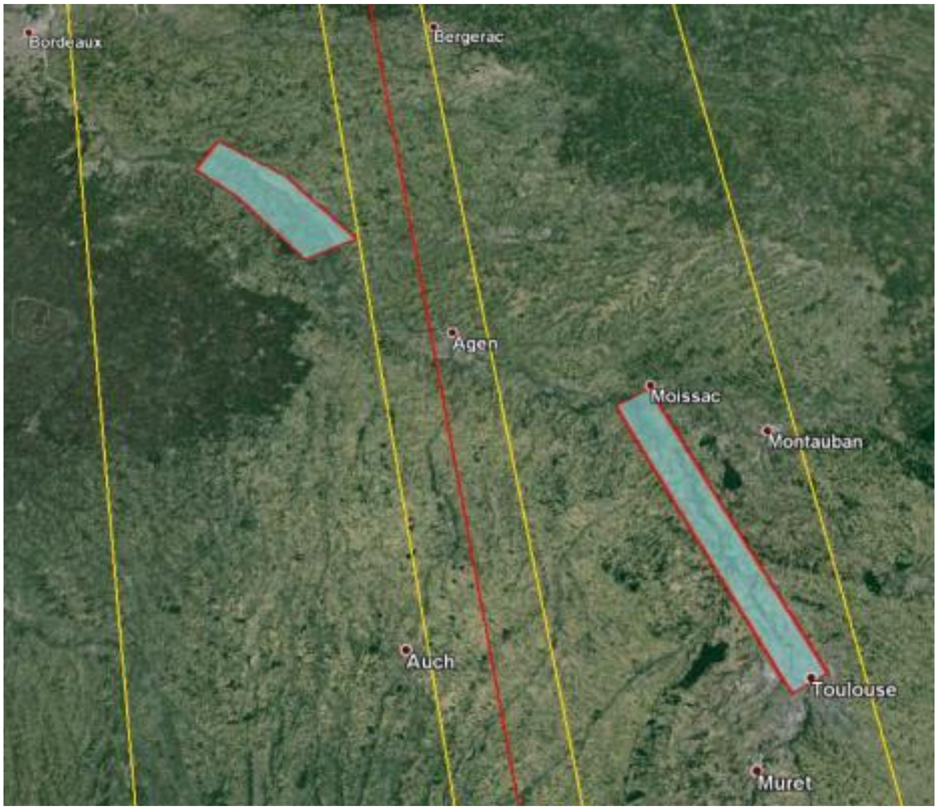


Figure 42. Cal/Val Garonne reaches and SWOT 1 day orbit swaths coverage (delimited by yellow lines, red line corresponds to the satellite nadir)

On these two reaches, the river channel is well defined (the river is not braided), no main tributary joins the river within the reaches (the Tarn river join the Garonne few kilometers downstream the Blagnac-Malause reach and the Lot river a few kilometers upstream the Tonneins-La Réole reach). There is riparian forest on the river banks, but the surrounding floodplain is mainly crops covered. Along the river banks, many levees were built to avoid flooding. The Garonne River valley is less than a dozen of kilometers wide (varying between reaches), steep-sided by hills (up to about 100 m higher than the valley) that generate errors due to layover effects.

7.2.1.2.2 Site Goals

These sites will be used to validate: water surface elevation locally and at multiple points, water surface slope along the river, discharge algorithms efficiency.

7.2.1.2.3 Site Instrumentation

On the upstream reach (Figure 38), there is one operational gage located in the middle of the reach (at Verdun-sur-Garonne), another one situated just upstream of the reach (at Portet-sur-Garonne) and a last one about one dozens of kilometers downstream of the reach (at Lamagistère, but beyond the confluence with the Tarn River). Water levels are measured every 15 minutes and the ellipsoid height of the gage is available for Verdun-sur-Garonne and Lamagistère stations (not available at Portet-sur-Garonne, but it can be done easily). Discharges from rating curve are also available from operational agencies.

Similarly, on the downstream reach three gage measurements are available (at Tonneins, Marmande and La Réole, see Figure 43), with the same measurement characteristics as for upstream gages.
These six gages are maintained by operational governmental agencies in order to alert in case of flooding or extremely low flows. There is therefore a very high probability that these gages will still be operational when SWOT will be flying and the data will be available for Cal/Val activities.

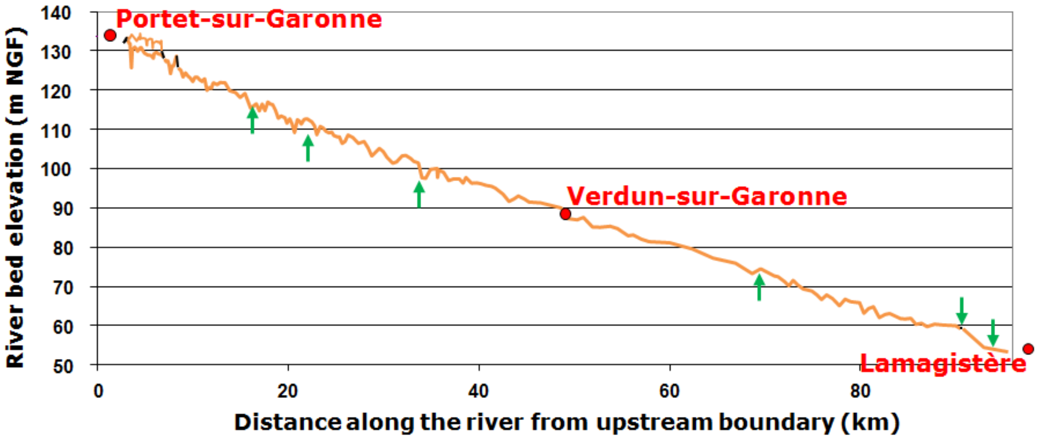


Figure 43. Longitudinal profile along the river axis for the upstream reach showing available river bed elevation (from bathymetric cross-sections). Red dots show current operational gages. Green arrows show water surface slope break, where additional GPS measurements could be done. Credit: IMFT

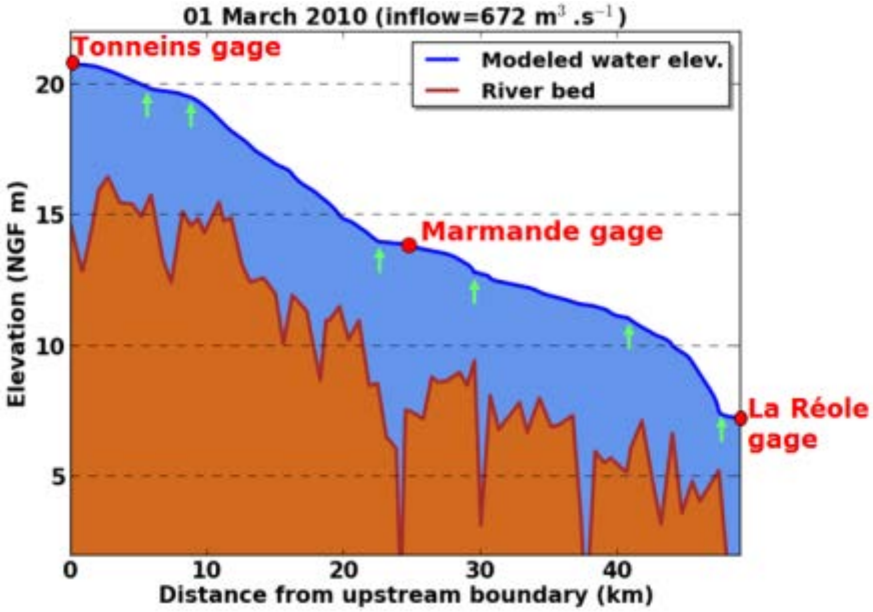


Figure 44. Longitudinal profile along the river axis for the downstream reach showing available river bed elevation from cross-sections, water surface elevation for 01 March 2010 from Mascaret model. Red dots show current operational gages. Green arrows show water surface slope break, where additional GPS measurements could be done. Credit: LNHE/CERFACS

On the upstream reach, 203 bathymetry cross-sections are available and have been used to set up a 1D and a 2D hydrodynamic modelings of the reach. Some of these cross-sections are quite old (~1995) and they should be updated. Moreover, they were not originally georeferenced, so it was necessary to do this more or less precisely by fitting with lidar data. A lidar DEM of the floodplain was provided by IGN (but unfortunately not scanned during low water level) and has been included in the 2D modeling by IMFT.

On the downstream reach, 83 bathymetry cross-sections are available, but here also they are quite old and need to be updated. 1D and 2D hydrodynamic modeling of the reach is also available. The floodplain lidar DEM is also available on this reach but needs to be included in the 2D hydrodynamic modeling.

7.2.1.2.4 Pre-launch Site Characterization

A few years up to several months before launch, older existing cross-sections for the two reaches should be updated and georeferenced, and new ones should be made using ADCP (providing bathymetry and also local discharge, the value of which could be compared to rating curves estimates). The ellipsoid height at Portet-sur-Garonne gage will be measured. In addition, SWOT data simulation will be computed within ST activities and could be used to characterize zones that are expected to have highest errors (layover, water mask detection error, etc.). These zones could then be subject to more intensive monitoring during the post-launch Cal/Val phase. A precise DEM for these simulation could be brought to IGN if need be.

7.2.1.2.5 Post-launch Cal/Val Activities

On Figure 43 and Figure 44, green arrows show locations with bathymetry and water surface slope breaks. These locations are good candidates for additional GPS measurement of water level for some short period of time during the 1-day orbit phase. Water-surface slope measurements along the river could also be done with a similar system to the one shown on Figure 21 (if available).

Currently available resources from the involved teams (CERFACS, IMFT, IMT, INSA Strasbourg, LEGOS, LNHE, Meteo-France): one boat and one ADCP could be used by IMFT (providing they are available during the Cal/Val phase), a few GPS at LEGOS and some wind speed gages from Meteo-France (at some cost). Among all the laboratories, there are several well trained people for each kind of equipment (ADCP, GPS) and additional people (a dozen) with no field experience that could be available.

One operational agency (DREAL/SPC Garonne) could update their rating curves for our Cal/Val activities and could install few ephemeral gages (~3,000 euros/gage).

7.2.1.3 Lower Mississippi River (U.S. Project Site)

7.2.1.3.1 Site Description

The lower Mississippi is a very wide (~1 km) and low-slope (~7 cm/km) river. It was selected as a tier 1 validation site because it is easily accessible and relatively well-instrumented, along with being the largest river by discharge in North America. The study reach selected is between Vicksburg and Natchez, MS, a length of ~115 km (Figure 45). The river is primarily composed of 1-2 channels, with only a few meander bends and no active control structures within the reach. The river exhibits and annual cycle in flow, with maximum flow usually occurring in spring or early summer and minimum flow in the fall and winter (Figure 46). The site is sufficiently far downstream that it does not experience ice formation in the winter, making it a good target for year-round validation activities.

Figure 45. Location of the Lower Mississippi Field Site

7.2.1.3.2 Site Goals

The primary goal of this field site is to validate SWOT slope, height, and inundation extent measurements on a large, alluvial, low-slope river. The Mississippi is the only river in the Continental U.S. where this validation is feasible, given the size of the river and lack of control structures.

7.2.1.3.3 Site Instrumentation

There are currently gauges at either end of the study reach (Vicksburg and Natchez) operated by the Army Corps of Engineers to measure river stage. Discharge measurements are not available at these sites but are available ~200 km downstream at Baton Rouge, LA.

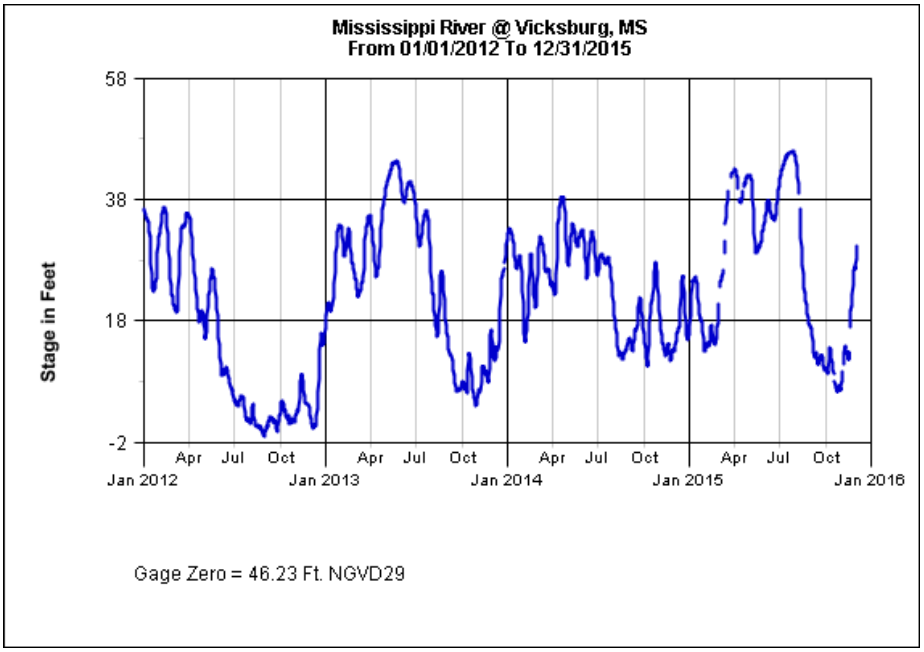


Figure 46. Stage hydrograph of the Mississippi at Vicksburg from 2012-2015.

7.2.1.3.4 Pre-launch Site Characterization

As a number of other river sites will be characterized prelaunch, it is not envisioned that a significant prelaunch campaign will be conducted for this site.

7.2.1.3.5 Post-launch Cal/Val Activities

The Lower Mississippi is not covered by the 1-day fast sampling orbit. As such, primary validation activities will take place after its conclusion. The most important SWOT variable to be validated at this site will be slope, since measurement errors for inundated area and height from SWOT are likely to be small given the size of the river. We will conduct four long-profile surveys of water surface elevation from a motorized boat as described in section 6.4.8. These surveys will be conducted from a motorized boat. In addition, two AirSWOT overflights will be conducted with long-profile surveys in order to assess the simultaneous accuracy of SWOT-derived height, inundation extent, and slope over the entire reach length. The USGS has a field office in the region and has the capabilities to conduct the kind of survey described here. It may be prudent to partner with them in order to complete these surveys in the most efficient way.

7.2.1.4 Connecticut River (U.S. Project Site)

7.2.1.4.1 Site Description

The Connecticut River Cal/Val site extends from the USGS gaging station at Thompsonville, Connecticut, USA, upstream to the USGS gaging station at Montague City, Massachusetts, USA (Figure 47). The river in this 80-km study reach is primarily gravel-bedded with a single-thread channel and relatively stable bed and banks, and one run-of-river dam located near Holyoake, Massachusetts.

There is extensive existing gage infrastructure, including three real-time mainstem and four major tributaries gaging sites operated by the USGS. The Connecticut River Cal/Val site is within the SWOT 1-day Fast Repeat Orbit, and is directly upstream of the Connecticut River Tidal Cal/Val site. Though there are small flow regulation reservoirs in the upper watershed, the hydrograph of the river is typical of temperate rain- and snow-fall river systems, with distinct and large regular peaks and recession limbs from October to June and a low flow period in the summer from July to September. In addition, this reach of the Connecticut River freezes during the winter, with breakup occurring in March or April.

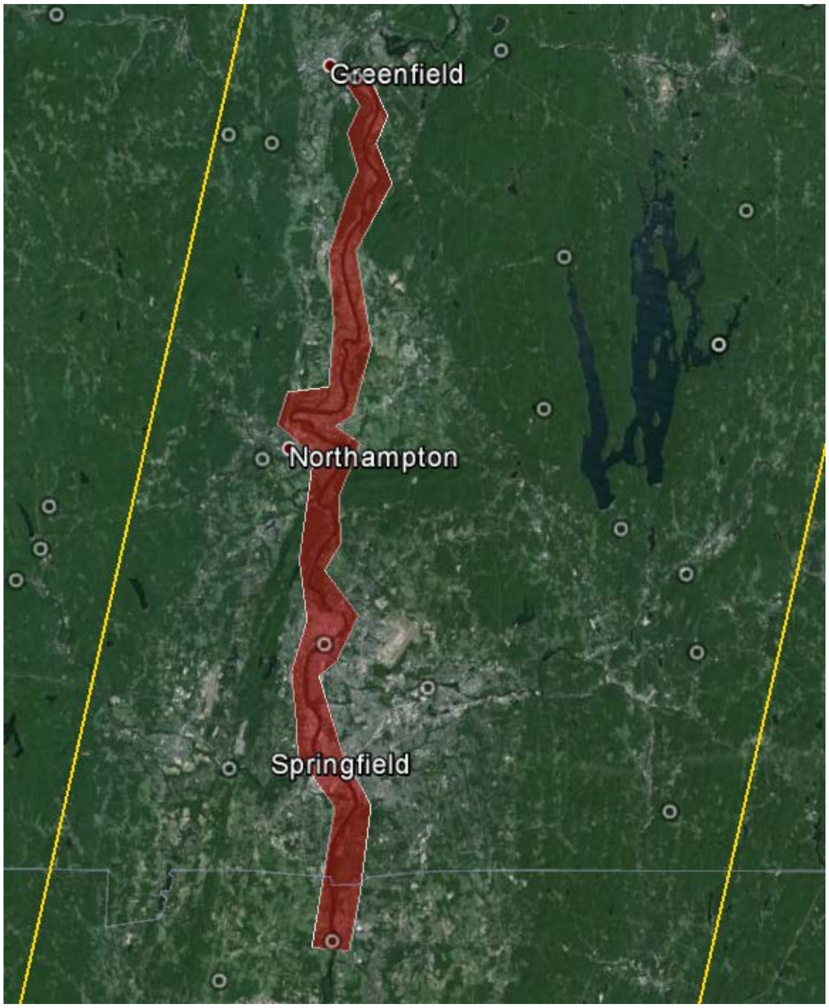


Figure 47. Map of the Connecticut River Cal/Val site, Connecticut and Massachusetts, USA. The two yellow lines show the extent of the KaRIN footprint during the 1-day Fast Repeat Orbit, the red area is the study reach, and the white-encircled symbols are USGS gages.

7.2.1.4.2 Site Goals

The Connecticut River Tidal Cal/Val study site will be used validate SWOT's ability to measure or characterize water-surface elevation, slope, inundation extent, and discharge as well as validate SWOT's layover-, ice- and rain-flags.

7.2.1.4.3 Site Instrumentation

There are three real-time mainstem discharge gages on the mainstem Connecticut River in the study reach, and four discharge gages on the major tributaries, all operated by USGS. All of these gages rely on rating curves for computing discharges, though discharge is measured at each site from ten to twenty times per year. During periods of ice accumulation, the records at the gaging stations are flagged in the USGS data record (see Figure 48). Several aerial lidar data collections have been flown over the study reach, including two FEMA flights in 2004, a post-Hurricane Sandy USGS flight in 2014, and a USGS 3DEP flight in 2015. The high-resolution DEM products from the 2014 and 2015 flights are expected to be completed in early 2016.

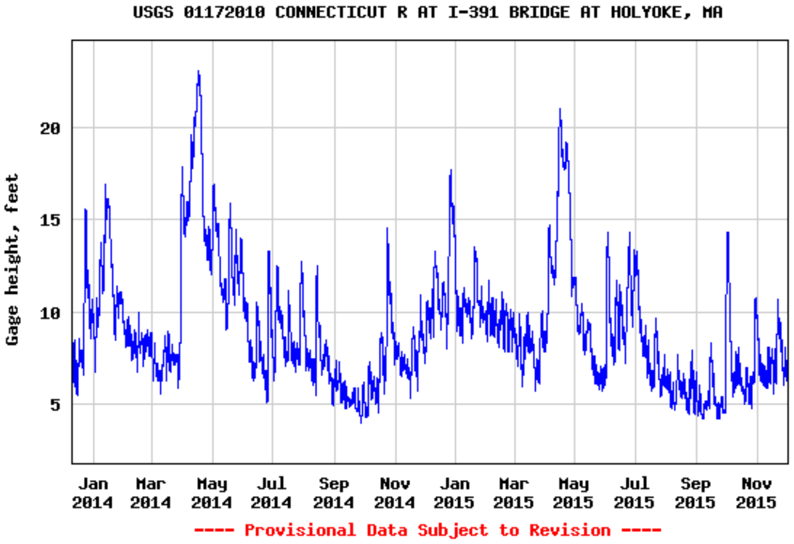


Figure 48. Gage data from the USGS gage on the Connecticut River at Holyoke, MA. The top panel shows river discharge, including ice flags, and stage for the corresponding period is shown in the bottom panel.

7.2.1.4.4 Pre-launch Site Characterization

The pre-launch site characterization of the Connecticut River Cal/Val site includes a short AirSWOT campaign consisting of two-days with multiple AirSWOT passes during various river stages scheduled for 2018. Concurrently, a ground campaign will have installed and levelled approximately 30-50 pressure transducers, as well as collecting day-of-flight longitudinal water-surface elevation and discharge measurements using coupled GNSS and ADCP instruments. If not performed previously, GNSS-leveling of the existing USGS gages will be required pre-launch. SWOT flagging will be evaluated using existing high-resolution lidar DEMs for layover flags, satellite-observations of ice and snow for ice flags, and local radar and weather stations for rain flags. In the months immediately preceeding launch, approximately 30-50 pressure transducers will be installed for the one-day fast repeat orbit.

7.2.1.4.5 Post-launch Cal/Val Activities

The post-launch Cal/Val activities for the Connecticut River site include monitoring the installed pressure transducers during the one-day fast repeat orbit, as well as two one-week campaigns for boat-based longitudinal water-surface elevation and discharge measurements.

7.2.1.5 Tanana River Validation Site (US Project Site)

7.2.1.5.1 Site Description

In Alaska, SWOT validation efforts will focus on two regions that will have received prior SWOT-related study: the Tanana River and the Yukon Flats (See section 8.2.2.X). The Tanana is a large braided river draining the northern portions of the Alaska Range (Figure 49). Because it receives substantial inflow from glaciers it also transports large sediment loads both in suspension and as bedload. As such, the channel planform changes rapidly in time and space. The Tanana is >1000 km in total length, but validation efforts will focus principally on a ~150 km reach in the vicinity of Fairbanks. This reach begins with a highly braided planform but transitions into a single-channel planform due to the influence of topography to the north of the river. As such, within this single reach it is possible to validate SWOT's ability to detect water surface elevation, slope, and inundation extent under many different conditions characteristic of northern rivers. The site was characterized in detail during a summer 2015 field campaign, including multiple AirSWOT overflights, field data collection of temporally continuous water surface elevation measurements at 23 locations, measurement of water surface elevation profiles down the entire region shown in red in Figure 49, installation of corner reflectors, and measurement of data related to Ka-band radar phenomenology. In addition, a 2-D hydrodynamic model based on LisFLOOD-FP has been developed using interpolated data from an in situ bathymetric survey conducted in 2013 by SWOT cal/val team members.

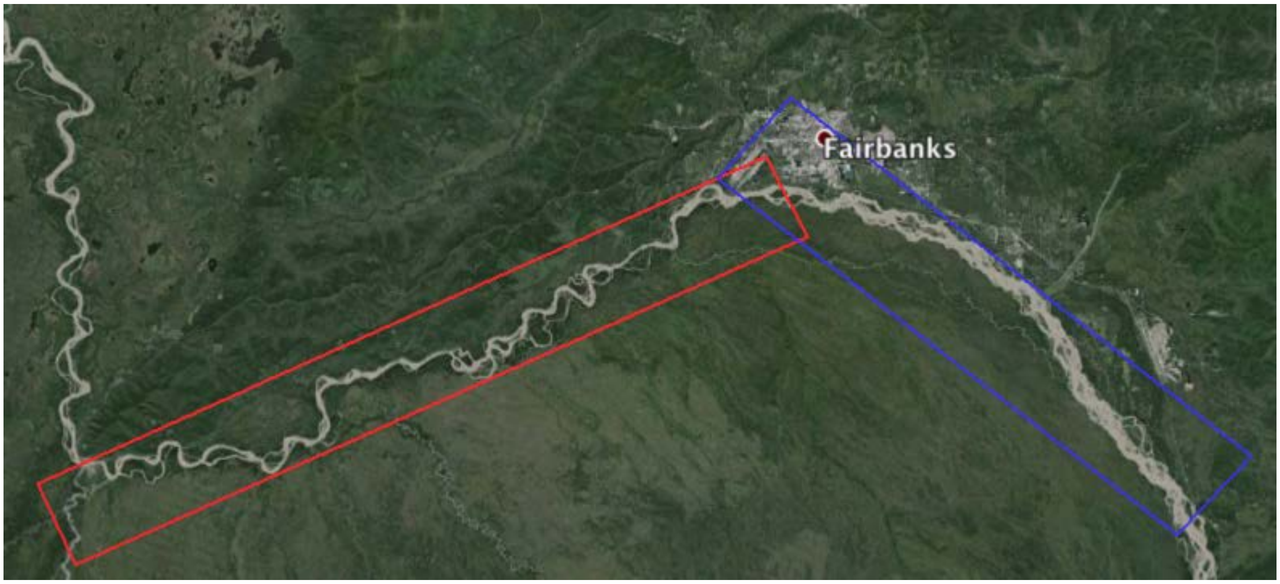


Figure 49. The Tanana River Validation Site

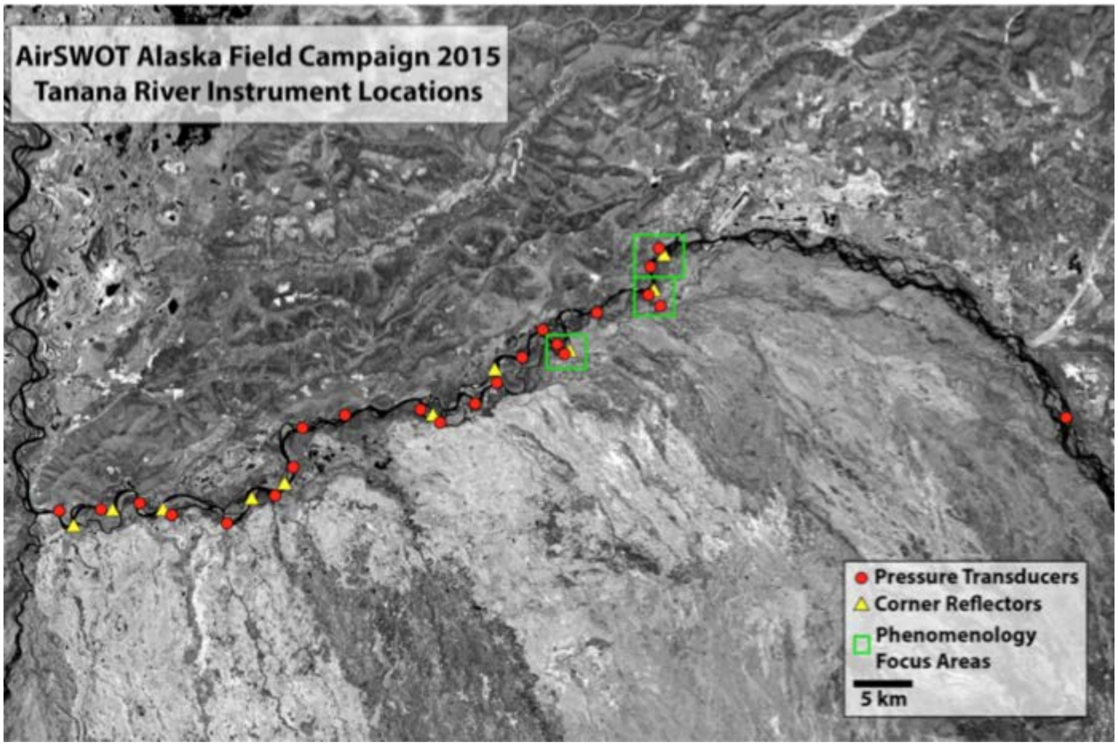


Figure 50. The Tanana River Validation Site, as characterized during Summer 2015

7.2.1.5.2 Site Goals

There are three primary validation goals for the Alaska sites:

1. Validate SWOT's ability to measure or characterize rivers with complex, braided planforms, such as the Tanana River. Characteristics to be studied include inundation extent, water surface elevation, and slope.
3. Test SWOT river discharge measurements in multithreaded and braided river environments.
4. Understand SWOT capabilities to accurately flag river ice.

7.2.1.5.3 Site Instrumentation

On the Tanana River, there are currently two operational discharge gauges, one at Fairbanks and one at Nenana, approximately 90 river km downstream. These gauges will allow for validation of discharge algorithms on the Tanana. Beyond these two gauges, however, there is no permanent instrumentation on the study reach. However, an airborne IfSAR DEM at 5 m spatial resolution is available over the entire study reach. In addition, data collected during the 2015 field campaign can be used to characterize the overall patterns of slope, height, and width that SWOT will likely observe on the Tanana, absent major planform changes between now and the Cal/Val period.

7.2.1.5.4 Pre-launch Site Characterization

Fieldwork to characterize the Tanana River study area began in 2013 with a bathymetric survey of the ~90 km between Fairbanks and Nenana. This allowed construction of a 2-D hydrodynamic model for the reach, which can help with validation. Substantial additional data was collected in summer 2015, including water level variations at 23 locations via pressure transducer (Figure 50) and 8 AirSWOT overflights of the entire study area, including both KaSPAR data and digital infrared camera imagery. Vegetation conditions and sand bar characteristics, including grain size and soil moisture, were also be collected, as were long profiles of water surface elevation measured using a precision GPS mounted on a Sontek Hydroboard.

7.2.1.5.5 Post-launch Cal/Val Activities

Cal/Val activities after launch will focus on the first summer post-launch. Because the currently planned 1-day repeat orbit does not intersect the Tanana Tier 1 Site, no effort will be made to conduct validation activities during this 3 month sampling period. For the Tanana River, validation activities will focus on the capabilities of SWOT to measure inundation extent, water surface elevation and slope and to estimate discharge. Aerial near-infrared imagery will be collected coincident with SWOT overflights in order to provide validation of inundation extent. A series of pressure transducer water level loggers will be installed along the Tanana in order to provide estimates of variations in water surface elevation and slope. Discharge can primarily be validated using the two stream gauges at Fairbanks and Nenana, but additional measurements will be collected by ADCP as necessary.

In addition to these basic measurements, two additional sets of measurements would provide desirable validation capabilities. AirSWOT measurements would provide full, 2-D validation of SWOT water surface elevations in both the Tanana River and Yukon Flats lakes. Airborne L-band SAR (e.g. UAVSAR) would provide robust measurements of water surface extent under vegetation in the Yukon Flats, which would offer a substantial improvement over ground-based surveys.

Finally, because of its proximity to Fairbanks, the Tanana will be used to validate the SWOT ice flag. Airborne visible and near infrared imagery will be collected simultaneous with a SWOT overflight during ice breakup, which will provide direct validation of SWOT's ability to differentiate ice from open water.

7.2.1.6 Canadian Validation Sites (Canadian Cal/Val Sites)

7.2.1.6.1 Site Description

In tandem with the USGS and ST members, Environment Canada will propose the following sites
1.The Peace-Athabasca Delta (PAD) and Lake Athabasca
2. The Yukon Porcupine River from Whitehorse/Yukon to Stevens Village/ Alaska
3. The St. Lawrence River near Trois Rivieres
4. The North Saskatchewan River at Prince ALbert
5. The Mackenzie River at Inuvik
6. The Slave River at Great Slave Lake

EC will lead these efforts with USGS support along with other international partners including ST members. Of the above sites, 3 will be Tier I sites: the PAD, the Slave River and the St. Lawrence, described briefly below. The rest of the sites will focus on validation of select SWOT observations, as described in the following section. These sites cover a broad range of physiographic and climatic regimes, from permafrost-free temperate (St. Lawrence) to continuous permafrost Arctic (Mackenzie) and discontinuous permafrost subArctic (Slave River).

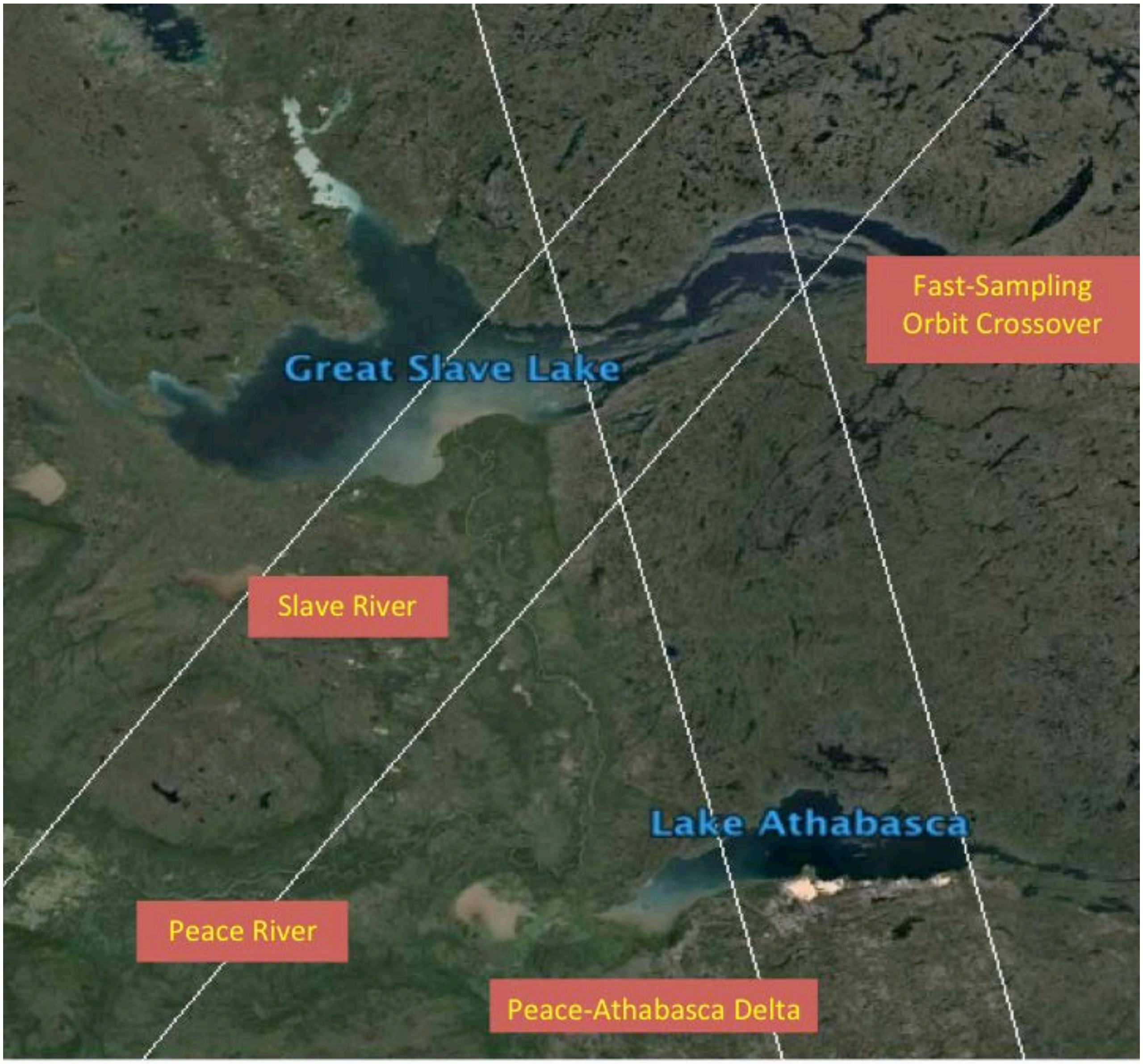


Figure 51. Map of the PAD.

The PAD is located in northeast Alberta. It is the largest freshwater inland river delta in North America. The delta encompasses around 5800 square kilometers and is formed where the Peace and Athabasca rivers converge at the west-end of Lake Athabasca and drain north via the Slave River. Two main Northern Cal/Val sites are located in this complex region. The PAD was designated a wetland of international importance under the Ramsar Convention in 1982. About 80% of the area is protected within the Wood Buffalo National Park (established 1922), which was designated a UNESCO World Heritage site in 1983. Given the international importance, the PAD has been the subject of many studies by Canadian agencies - mostly Parks Canada, Environment and Climate Change Canada (EC) and Natural Resources of Canada (NRCAN) – and universities. The PAD drains northward in the Slave River which has a stable flow rating curve and a long history of flow records.

The river gauge is upstream of a natural control and has few tributary input at the proposed cal/val section.

Figure 52. The Peace Athabasca Delta (PAD) delimited by Lake Claire to the West, the western end of Lake Athabasca to the East, the Peace and Slave rivers to the North and the Athabasca River to the South.

The St. Lawrence River is the third largest river in North America, with a catchment area of ~1.6 × 106 km^{2}, and an average freshwater discharge of 12 200 m3s-1 at Quebec City. It is the downstream water body of the Great Lakes and Ottawa River systems and it is subject to large variability at all scales. While decadal time scale variability is caused by climate dynamics, management of its upstream sources can significantly impact water levels at the seasonal time scale, in particular in the Montreal archipelago.

Between Montreal and Trois-Rivières, more precisely downstream of Sorel, the river widens significantly. The area, known as Lac Saint-Pierre, is a UNESCO biosphere reserve. This ecosystem is host to a vast number of migratory birds, and sustains an important recreational and commercial fishing industry. Downstream of Trois-Rivières, significant tidal influences are observed, with water level differences between low and high tide of over 5m at Quebec City. Strong current reversals are observed, combined to rapid changes in wetted areas over shallow topography, as a result of these variations.

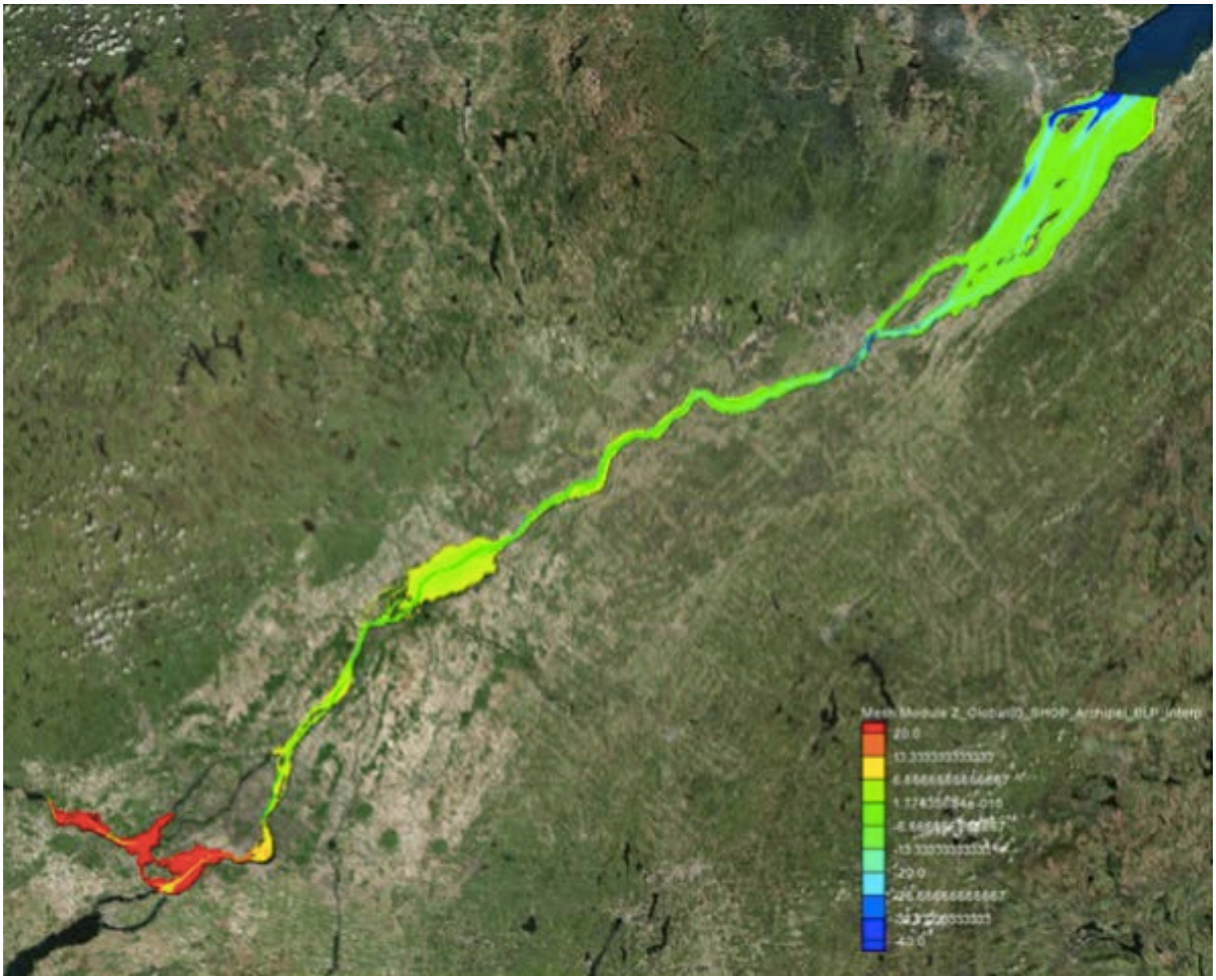


Figure 53. Topography of the St. Lawrence River, including the Montreal archipelago, Lac Saint-Pierre and the fluvial estuary down to Île-aux-Coudres.

7.2.1.6.2 Site Goals

At all sites, gauge data will be used to characterize water elevation, local slopes and in manycases SWOT-derived discharge. Each site will also validate SWOT height, slope, and inundation area. The Tier I sites will validate these quantities over greater areas and with greater precision, and include meteorological stations and deployments to the field concurrent with a SWOT overpass. Collectively, the sites will also validate SWOT's performance vis-a-vis permafrost controls, which introduce complex bank morphology and potentially very wet soil when thawed.

Another goal across these sites is to develop and contribute to a standard methodology for making cal/val measurements, and EC and the ST are set to begin making pre-launch measurements as early as 2016 to test the protocols outlined in this document. Where possible these sites are co-located where EC already has existing hydrodynamic models established or in operations.

7.2.1.6.3 Site Instrumentation

EC maintains a vast network of river gauges, and gauges are located either within, adjacent upstream or downstream, or adjacent both upstream and downstream to all proposed sites. EC also maintains several hydrodynamic models of various rivers.

Specifically, for the PAD, The Water Survey of Canada established hydrometric stations in the early 1970s and seasonal pressure transducers for research purposes enhance the long-term monitoring network. Historical and present water extents based on remote sensing technology are also available. Elevation benchmarks for the hydrometric have been converted to the new geoid-based vertical datum CGVD2013 with high precision GNSS surveys. Using any global geoid model is thus already a possibility on this site.

LiDAR data over the PAD is available on a portion of the PAD; surveys were flown in 2000, 2012 and 2013, with the rest of the area covered by lower resolution Space Shuttle Topography Mission (SRTM) data.

Vegetation characterization has also been done over a portion of the site via more than 35 vegetation transects maintained by Wood Buffalo National Park since the 1990s.

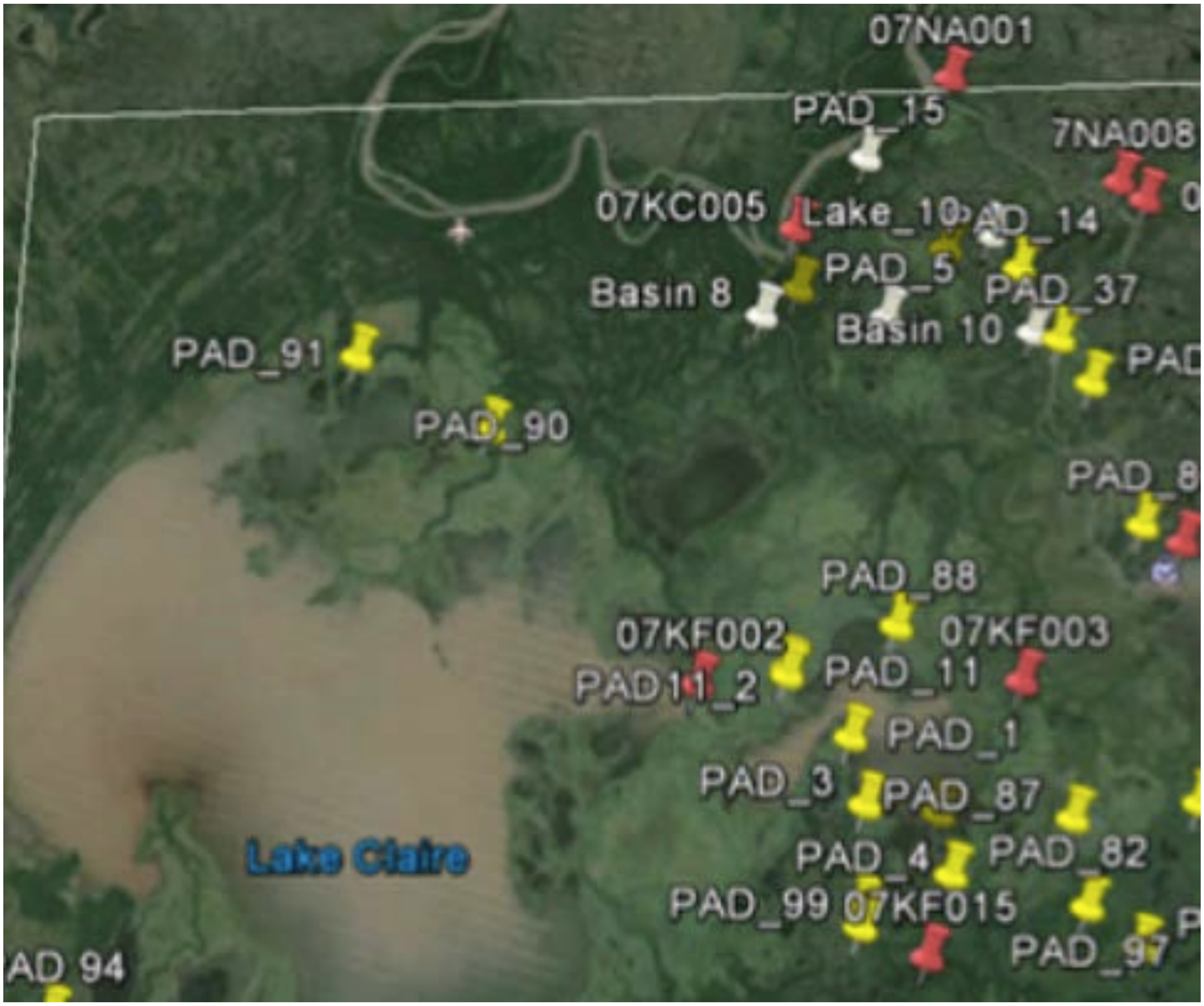


Figure 54. Available seasonal pressure transducers(white and yellow) and permanent hydrometric station (red) over the PAD region.

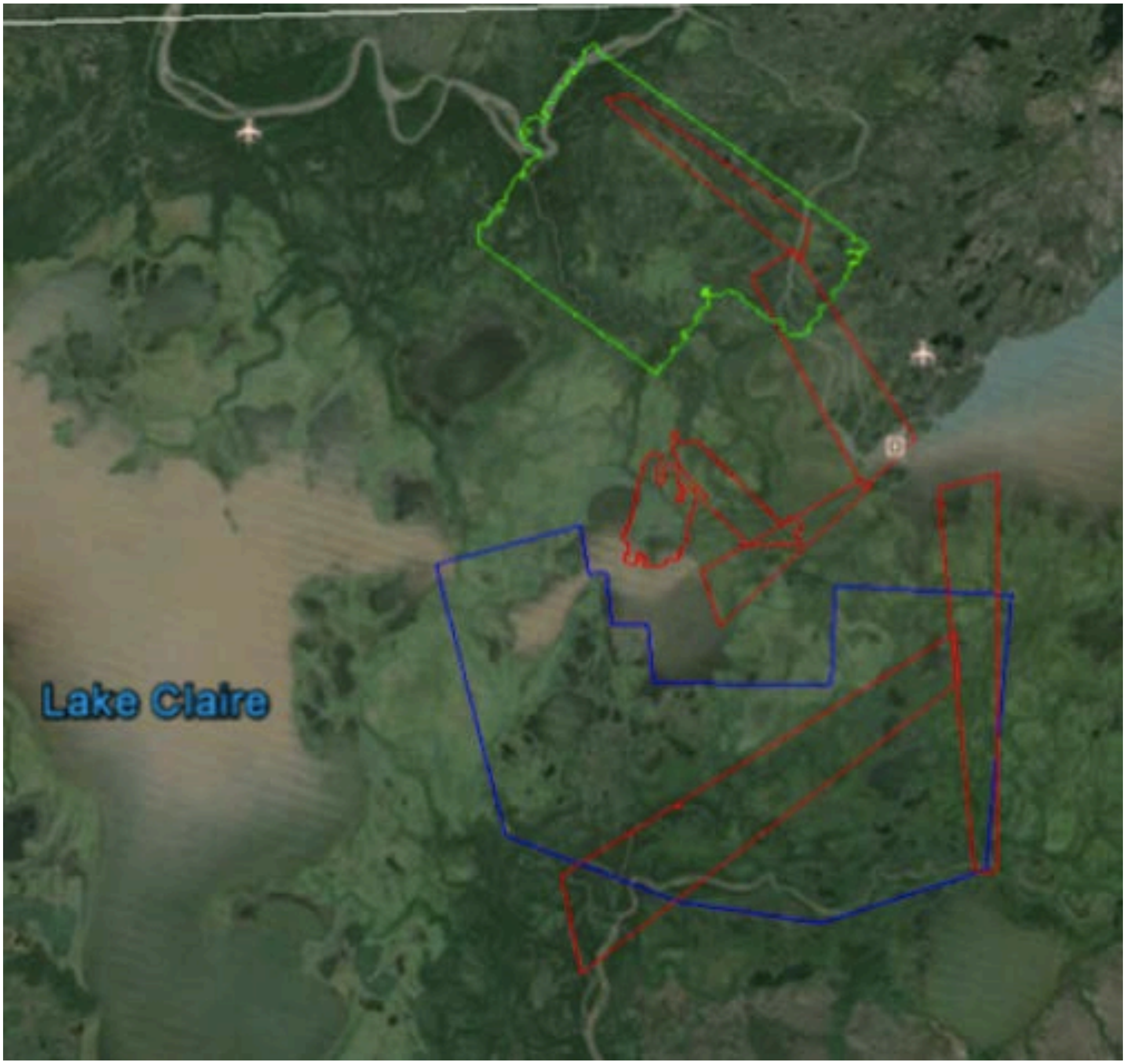


Figure 55. LiDAR data potentially available over the PAD region. Surveys were done in early 2000 (red), 2012 (green) and 2013 (blue).

There is a great amount of satellite imagery available over the PAD from 2008 up to this day. Lidar data is also available over parts of the PAD and the St-Lawrence seaway. Radarsat 2 imagery is almost guaranteed to be available over the PAD on a periodic basis, giving access to hi-resolution imagery data for water extent mapping regardless of the conditions (unlike optical imagery). There is also the possibility of running a 2D hydrodynamic model over the whole PAD region in the coming years that might also be available before the launch. Wind forecast models - which are being verified for inclusion in the 2D hydrodynamic model over Lake Champlain in non-stationary mode - can potentially also be verified over the PAD to assess the effect of wind over the sites. Lake Athabasca heights will be available in CGVD2013 (Geoid CGG2013) . Wind forecast models - which are being verified for inclusion in the 2D hydrodynamic model over Lake Champlain in non-stationary mode - can potentially also be verified over the chosen lakes to assess the effect of wind over the sites. Lake Athabasca heights will be available in CGVD2013 (Geoid CGG2013)

In the case of the St. Lawrence, a detailed hydrodynamic model able to provide water level, currents and temperature information is available from Montréal to Quebec City, with an average spatial resolution of 190m and refinements down to a few meters. Between Montreal and Trois-Rivières, accuracy of water level predictions is on the order of a few centimetres. Downstream, errors in water levels are below 5% of the local tidal ranges. A hydrologic model calculating the total inflow to the river from the Great Lakes to Quebec City is also available from the Centre Météorologique Canadien (CMC).

The site has permanent hydrometric stations covering the entire domain that provide real-time water level and discharge (few sites only) data (Figure 56). Maps of the floodplain, emerging, aquatic and shore vegetation, substrate, roughness as well as derived manning coefficients are also available. LiDAR and bathymetric surveys were conducted during the 2000s to get a high resolution DEM of the whole area.

As of this day the model runs in stationary mode between Montréal and Trois-Rivières on a daily basis on the CMC computers. The entire system, including the tidal part of the river, is pending completion. Predictions of water levels are also available on the whole domain from an operational one-dimensional model. A 2D hydrodynamic model of one of the river tributaries, the Richelieu River, is already available

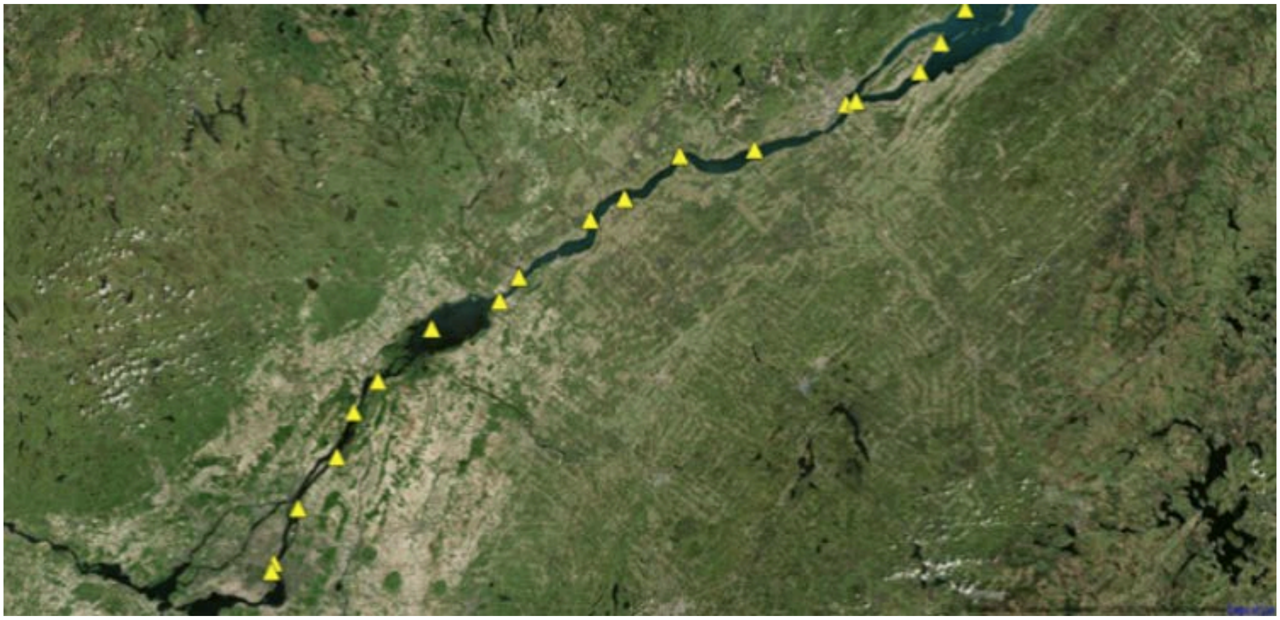


Figure 56. Permanent and seasonal hydrometric stations on the St. Lawrence River.

7.2.1.6.4 Pre-launch Site Characterization

At each site, EC and the ST will install networks of pressure transducers to validate SWOT height measurements along river channels. These transducers can also be calibrated with in the field discharge measurements to make a network of gauges, and this will be performed prior to launch at least at the Tier I sites, and this information will be used to develop well calibrated discharge algorithms for the sites. At the Tier I sites, these will be permanent installations, surveyed into place using GNSS GPS, and left in place until at least the end of the fast-sampling phase. In early September of each year the installations will be revisited for data download. This effort will be led by EC, using EC boats, equipment, and field technicians. Also at the Tier I sites, meteorological stations will be installed prior to the fast sampling phase to understand both energy balance for a more complete hydrologic understanding of the basins and to validate SWOTs rain flags.

In addition to the above, specific measures will be looked at for the PAD. High precision fieldwork was conducted during the 1990s and resumed in 2010 with new ground LiDAR surveys, enhanced water level monitoring, characterization of surface water connectivity, and should intensify in upcoming years for the SWOT program. Work from both NRCAN and EC will allow the creation of a high resolution DEM extending further out of the floodplain and more towards the limits of the domain, allowing the creation of a 2D hydrodynamic model on the region which is being worked on by EC and the university of Sherbrooke. Water level monitoring on a permanent and seasonal basis is done every year on more than 25 sites and is planned to continue and expand to more sites as part of the Joint Alberta-Canada Oil Sands Monitoring Program. A UAV overflight for validation of a SAR surface water and flooded vegetation product was conducted in 2015 by NRCAN. Corner reflectors, meteorological data, bathymetric and single laser LiDAR were used during this survey and could help in the high resolution DEM creation. Radarsat-2 derived water extent detection over the region will be continued. It is planned to use ADCP and shallow water multibeam echosounder on the lower Athabasca River , along with high precision GNSS to characterize sensible areas on the river mainstem in 2016 and more is planned in the coming years for key connecting channels. A study of some of the lakes phenomenology (wind seiche, emergent vegetation, vegetation on lake margins, mud and floating vegetation, waves and low slope mud shorelines) and their effects on correct water level and extent measurements and instrumentation placement limitations will also be conducted. Wind forecasts model, along with measurements on site will also continue to be worked on to study wind seiche on different lakes in Canada, including Lake Athabasca.

Plans for the stretches along the St. Lawrence include permanent installation of an acoustic Doppler velocity meter (ADVM) in Quebec City, scheduled for installation prior to the SWOT launch. Temporary installation of the device has been tested and has shown satisfying results, providing real-time discharge values for the Saint-Lawrence. The use of a better hydrological (runoffs) estimation of the tributaries and the ungauged basins as an input to the hydrodynamic model is under testing and should improve the overall precision of the model. Pressure transducers will be placed in the tributaries to better estimate the hydrological delay between the hydrometric stations and the river. The hydrodynamic model of the site is scheduled to be run in non-stationary mode from Montreal to downstream of Quebec City by the end of the 2016-17 fiscal year. Predictions in non-stationary mode should be made available in the coming years. The International Great Lakes Datum of 1985 (IGLD85) is scheduled to be updated in 2018 and will be fixed to a geoid. This will make vertical information of the site easier to convert to the chosen vertical datum for the mission. Further field work to update and improve the current information about the site will be conducted when necessary.

7.2.1.6.5 Post-launch Cal/Val Activities

Depending on the time of year of the fast sampling phase, the Canadian / Northern sites are also opportune to validate SWOT's ice flags, and may provide a complex ice breakup environment for this validation. During SWOT's mission, remotely sensed datasets will be used to validate inundation area, and transducer installations from the pre-launch permanent installations will be used to validate SWOT height and characterize river discharge algorithms.

Specifically in the PAD, The fast-sampling orbit covers the western end of Lake Athabasca and to the North on the Slave River, the latter being another Canadian validation site. Detection of wind seiche will be possible along with more limited water inundation extent detection during this phase of the mission.

For the PAD specifically, during the science and fast sampling phase of the mission, Radarsat-2 derived imagery representing the water extent will be collected close to or coincident with SWOT overflights to validate water detection. Unlike optical imagery, this will provide water extent information regardless of the conditions. Pressure transducers will be installed on sensible inundation areas and small lakes as well as on the Peace, Slave and Athabasca mainstems to enhance the existing WSC hydrometric network to monitor water level variations. ADCP can be installed for discharge measurements where no permanent real-time hydrometric station is available. Ground-based surveys are also planned to better define inundated vegetation "shoreline" areas of water bodies and water elevation measurements and modelling.

In the ST. Lawrence, Radarsat-2 derived imagery of the ice and water extent close to or coincident with a SWOT overflight will be made available regardless of the meteorological condition as opposed to optical imagery. A CODAR HF radar system could also be put on site to get information about the surface current under the fast sampling orbit or elsewhere on the site. The fast-sampling orbit covers the tidal part of the river downstream of Quebec City. Water level and discharge data, as well as high-resolution (~200m average) 2D hydrodynamic simulations and predictions will be made available along with SWOT simulations. Ground based surveys will also be conducted to maintain the quality of the data provided during the whole mission and on an ad-hoc basis should the need for additional information arise. The final 2D hydrodynamic model will also be available to simulate SWOT overflight to provide other validation strategies prior to an actual SWOT measurement should an AirSWOT overflight be unavailable.

7.2.1.7 South American Validation Sites: South American Rivers (France & Foreign Partner Sites)

7.2.1.7.1 Site description

Working in South American rivers implies having research projects endorsed by local institutions. In order to set up projects and agreements with these local institutions, a group of SWOT early adopters was constituted, with a kick-off meeting held in May, 12-14th, 2015 in Rio de Janeiro, Brazil. A second meeting will occur in March 2018. The final list of sites, and their ranking as Tier-1 site, additional site, etc will ultimately depend on the projects and agreements that could be set up by launch, and by the funding available for these projects.

Three passes of the fast sampling orbit crosscut the South America continent, including the Amazon basin, the largest watershed in the world with thousands of contributor rivers of all sizes. This basin has long been used as a validation site for altimetry missions and most of the technologies proposed in this document for the validation over continental waters have been developed and tested in this basin. This includes installation of levelled gauges and profiles of free surfaces by GPS onboard boats. Today, more than 20,000 km of GPS profiles have been collected at different seasons over the major tributaries of the Amazon basin. It is established by Moreira et al. (in prep) that the accuracy of these profiles is at the 2 cm level at the 2 km horizontal scale. These profiles reveal the changes in height and slope along the profiles with the rise or fall in the hydrological cycle, in particular how far from the river mouth do the damping of the slope propagate because of the backwater effect. Today, these GPS profiles constitute the best way to derive continuous profiles of the free surface slope. Consequently, this technique of GPS systems embarked on large boats will be privileged in the Cal/Val operations dealing with the validation of heights and slopes in the South American rivers.

Figure 57. Coverage of Fast Sampling Orbit over south America. The course of the major contributors of the Amazon are shown in light blue.

Figure 58. Leveling of a gauge by direct observation with a GPS system on top of a gauge (foreground), and survey of the river height and slope with a GPS system installed on the roof of the boat (background).

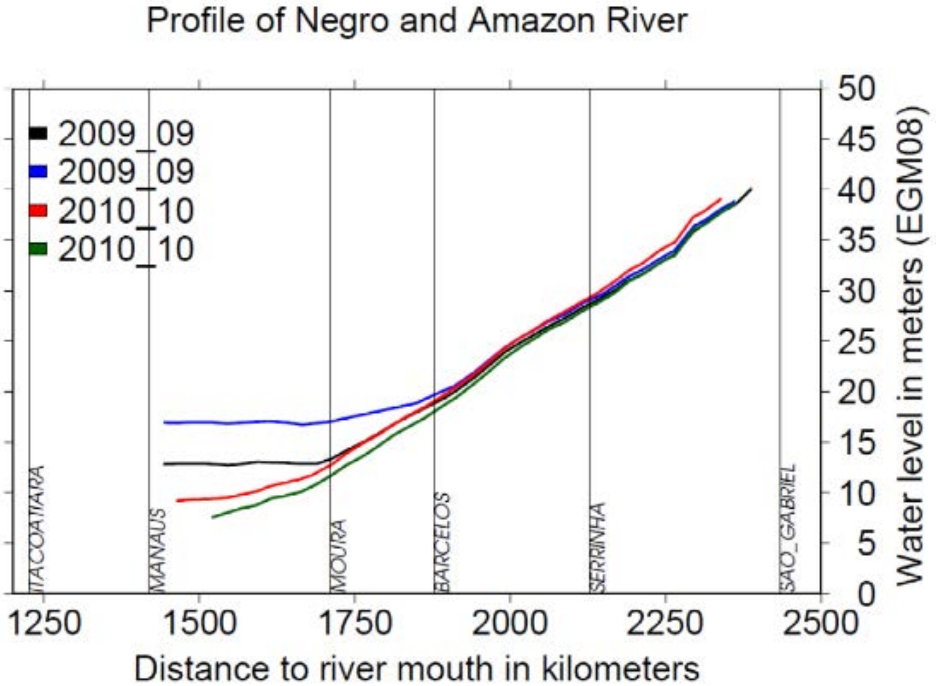


Figure 59. Example of GPS along the Negro river at different phases of the hydrological cycle. Note the flattening of the profile at the river mouth, due to backwater effect controlled by the level in the Amazon river itself.

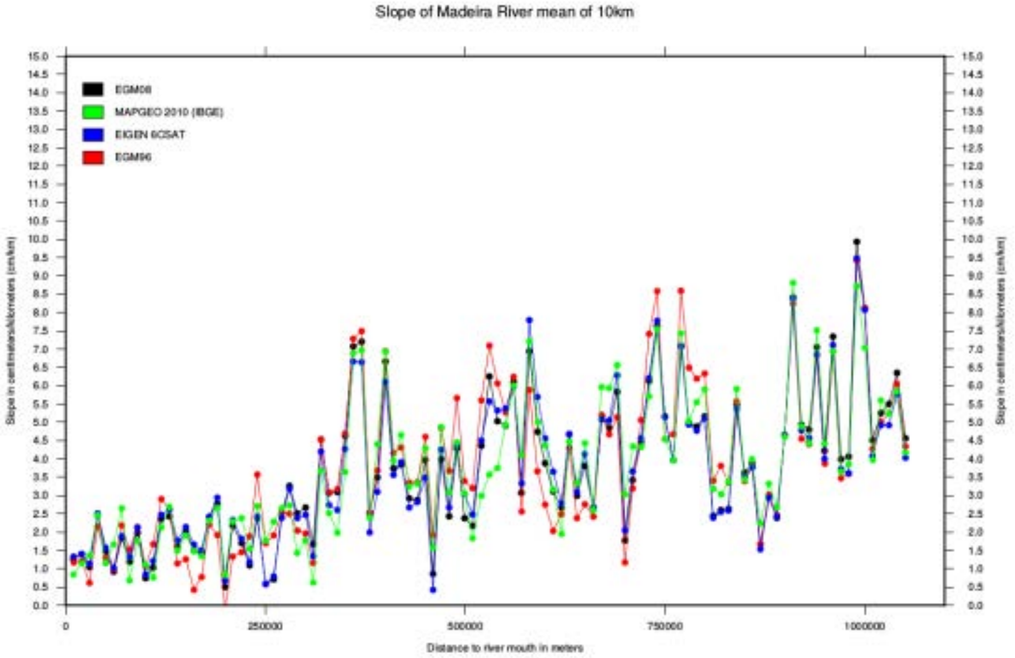


Figure 60. Longitudinal derivative of a GPS profile of the free surface of the Madeira river (averaged every 10 km), using different geoid models. Note that the major undulations exhibited by the slope profile are not significantly altered by the choice of the geoid model.

7.2.1.7.2 Site Goals

The South American sites will be used to:
- 1 validate the SWOT heights
- 2 Validate the SWOT slopes
- 3 check for long wavelength error. The Fast Sampling tracks of SWOT over South America will crosscut river reaches all along the pass. Joint analysis of the height errors all along the passes will be conducted to evidence possible long wavelength errors.
- 4 check for roll error
- 5 Characterize discharge

7.2.1.7.3 Site Instrumentation

Brazil maintains a network of hundreds of hydrometric stations throughout the country. These data are distributed freely and consequently they will be made available to the project. Specifically for SWOT, a list of priority stations that must be delivered in Near Real time will be established in the frame of a SWOT Early Adopters project.

The Andean countries collect water levels but today, they do not distribute the data publically. An agreement with the relevant organisations will be established between the French and US projects on one side and the local operators on the other side, in order that the data are made available at least during the Fast Sampling orbit. These agreements constitute one of the objectives of the SWOT early Adopters group.

7.2.1.7.4 Pre-Launch site characterization

All the sites that will be selected will have at least a pair of gauges in order that the roll effect can be evaluated. If not existing, these gauges will be installed.

All the gauges will be levelled. if not already done by local agencies, GPS levelling of the gauges will be performed before the launch of SWOT.

All the sites will have at least one measurement of the reach cross section. If not available from the local agencies, at least one ADCP measurement will be performed for the sites selected.

All the sites will have a stage - discharge relationship (rating curve). If not available from the local authorities, a rating curve will be established on a “best effort” basis using satellite altimetry and a rain-discharge model. As much as possible, the sites will be selected at crossings with other altimetric missions, in particular the Sentinel-3 missions. The water level series gained from these missions will be used to establish the rating curves.

A capability to send the in-situ information within a few will be established whenever necessary.
In the frame of the South American Early Adopter group, an effort will be carried out at the inter-agency level to level as much as possible the networks of existing gauges, with priority given to the gauges located into the swaths of the Fast Sampling orbit

7.2.1.7.5 Post-Launch activities

All the sites will be selected as to be overflown during the fast sampling orbit. During this phase, the in-situ stages will be collected daily at the time of overpassing. As much as possible, an ADCP measurement will be performed daily. It will provide the value of the discharge and reach width.
On a longer term, the SWOT heights will be compared to the series of vertically referenced water levels collected at the gauges levelled prior the the launch.

For many stations, the data are collect by means of a technician hiring a boat to go from one station to the other. As much as possible, these cruises will be conducted at the time of overpassing by SWOT since they will be used to collect profiles of the free surface by means of GNSS station installed on top of the boat (or trailed behind the boat). These profiles will be computed using CNES’ software GINS-PC and used to assess the SWOT slope products.

7.2.2 Lake Cal/Val Sites

7.2.2.1 Lake Issykkul Validation Site (French Project Site)

7.2.2.1.1 Site Description

Lake Issykkul is located in Central Asia, in Kyrgyzstan, and serve officially since 2008 as a Cal/Val site for satellite altimetry on Jason-2, Envisat, SARAL/AltiKa and future nadir altimeters. It has a length of 180 km and a width of about 60/70 km. West part of the lake’s shoreline is very shallow, while east, north and south part is covered with high mountains. It is the region of the world the most far from any ocean. Well located in the center of the Eurasia it will be a perfect location for additional site for calibration of cross track error in particular to roll and phase error. The seiches are not frequent, not too high (generally smaller than 10 cm) and they could be monitored as they are preferentially oriented in the East/West direction: an in situ gauge with data time sampling of 5 minutes is already installed in the East side of the lake where the effect is the highest. The access is quite easy thanks to 10 years of collaboration between Legos and Kyrgyz institute of hydrology. Vessel for navigation over the entire lake is possible all the year at a reasonable price for such boat. Based on more than 10 years of collaboration with local authorities which has been confirmed for the following years, a Mean lake surface at high spatial resolution is under construction.

It is large enough to be crossed by SWOT several times over each cycle of 21 days. Lake Issykkul, in the half east part will be fully covered by SWOT during the 1-D orbit fast sampling. Lake Issykkul has been instrumented with permanent GPS receivers, 2 water height gauges, and weather stations.

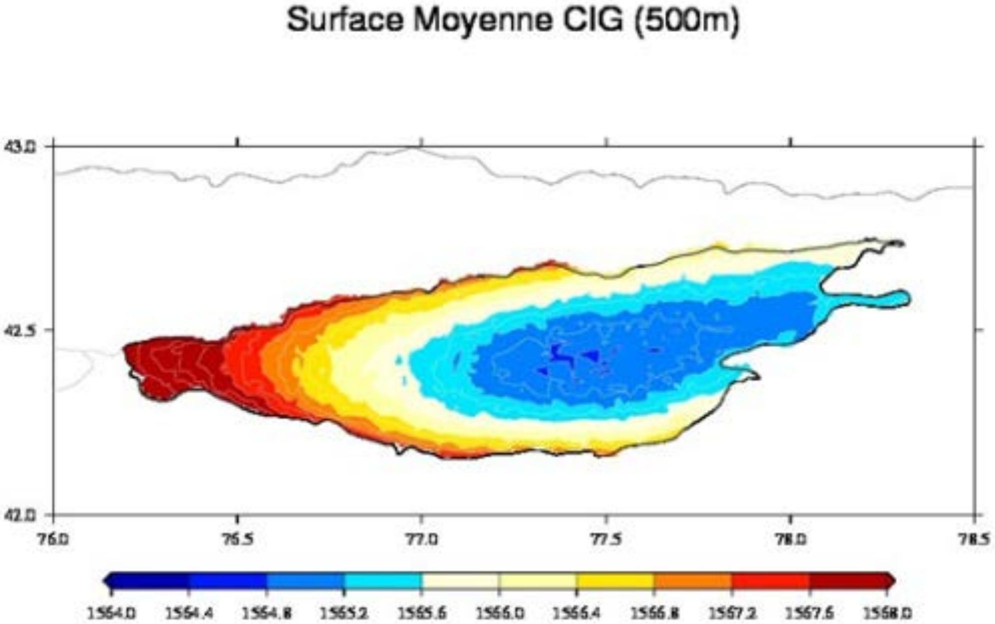


Figure 61. Preliminary mean lake surface of Issykkul from a combination of Cryosat-2, Icesat and GPS field works from 2004 to 2010. Work to be continued before the launch.

Figure 62. Lake Issykkul (from GoogleEarth) with 1D fast sampling orbit representation 'red: nadir, and yellow lines, swath's limits).

7.2.2.1.2 Site Goals

During the fast sampling 1D orbit, the Lake Issykkul will be used to
- validate height determination
- validate slope
- calibrate the roll and phase errors using a mean lake surface which will be inferred from about 15 years of field measurements with moving GPS over a 1km resolution on the entire surface of the lake.

7.2.2.1.3 Site Instrumentation

- Weather station at three locations
- 2 in situ level gauges, one with measurement twice daily, one with one measurement every 5 minutes
- 2 permanent GPS receivers
- Vessel available for fieldwork on the lake

7.2.2.1.4 Pre-launch Site Characterization

The main task for pre launch will be to complete the calculation of the mean lake surface by some additional fieldwork in the frame of OSTST program for Cal/Val of nadir altimeters

7.2.2.1.5 Post-launch Cal/Val Activities

During the 1D fast sampling phase:
- daily measurement of water level of the lake at the exact date of pass of the satellite
- installation of a GPS local network along the shoreline of the part of the lake covered by SWOT for determination of tropospheric delay
- monitoring of seiche effect using in situ data and wind field measurements (network of anenometer will be temporary installed)
- GPS kinematic profile on the cross track direction right over the Swath to calibrate for roll and phase error and compare with mean lake surface

During the nominal phase:
- compare pass per pass the water level measured with SWOT with in situ measurement
- compare the mean lake surface measure by SWOT with those obtained from the historical GPS fieldwork.
- use these vertical profiles between the nadir and the swath to check the consistency between KaRIN and the nadir altimeter avoiding any errors due to interpolation within the nadir gap.
- Using in situ water height at high temporal resolution (5 minutes) and the mean lake surface will also allow calculating the static range biases of both KaRIn and the nadir altimeter.

7.2.2.2 Lake Tahoe Cal/Val Site (U.S. Project Site)

7.2.2.2.1 Site Description

The Lake Tahoe Cal/Val Site is located at Lake Tahoe on the border of California and Nevada, USA (Figure 63). Lake Tahoe is located at relatively high altitude, 1,900 m, and is relatively large with a surface area of approximately 490 square kilometers. Lake Tahoe is a good location for a Cal/Val site due to the large amount of compiled data and active research on the lake. Active research on the lake that is of particular interest to SWOT is that done by the U.C. Davis Tahoe Environmental Research Center, TERC (http://terc.ucdavis.edu/), which includes a network of buoys and boat deployments, that are used in combination with JPL for calibration of other NASA satellites, such as Terra, Landsat, Aqua, and Envisat. The Lake Tahoe Cal/Val Site is not within the SWOT 1-day Fast Repeat Orbit, and as such, the post-launch activities primarily will take place during the Science Orbit.

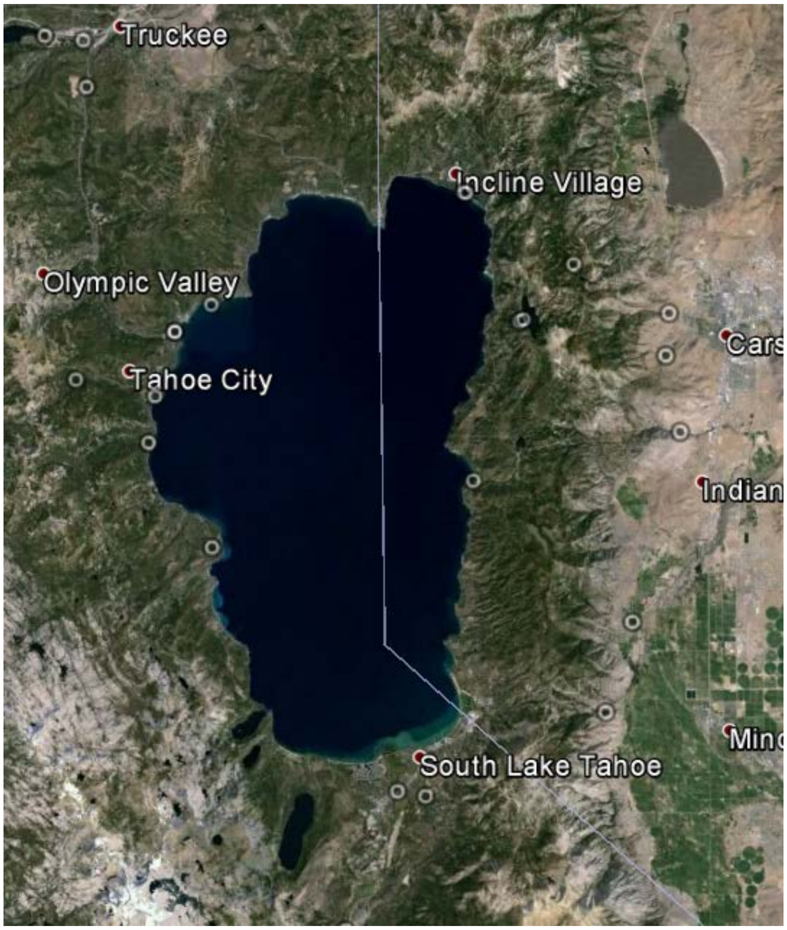


Figure 63. Lake Tahoe.

7.2.2.2.2 Site Goals

The hydrology goals of the Lake Tahoe Cal/Val Site are to validate SWOT measurements of absolute water surface height, and inundated surface area for a large, high-altitude lake. In addition, other components of the SWOT error budget may be validated here due to the unique properties of this site, such as random height error, range drift, and roll/phase drift.

7.2.2.2.3 Site Instrumentation

Lake Tahoe has a variety of *in situ* instruments, including several stage measurement devices (some operated by USGS, others by TERC/JPL, and US Coast Guard), several metrology stations (operated by NWS and TERC), inflow/outflow river gages at all the major tributaries (operated by USGS), and four stationary buoys (operated by TERC and JPL; http://laketahoe.jpl.nasa.gov/get_met_weather) that record atmospheric, radiation, and water quality data but not water stage data. In addition, a number of research vessels are available for making day-of-flight measurements. Aerial lidar for the full watershed was collected in 2010 and 2012 and high-resolution DEMs of the shoreline are available.

Figure 64. TERC/JPL stationary buoy in Lake Tahoe.

7.2.2.2.4 Pre-launch Site Characterization

The pre-launch site characterization of the Lake Tahoe Cal/Val Site was started in 2013 during the AirSWOT flights of that year. Those experiments included boat-towed buoys with GNSS stage measurements. Additional pre-launch characterization of the site will include supplementing the existing instrumentation with stage recorders (such as adding stage measurement capability to the existing stationary buoy instrumentation), as well as deploying approximately fifteen pressure transducers around the lake to study wind-driven changes in surface water elevations across the lake if these data have not been previously collected. Because Lake Tahoe is not under the 1-day Fast Repeat Orbit, no immediate pre-launch setup will need to take place. Instead, the pressure transducers will be deployed post-launch.

7.2.2.2.5 Post-launch Cal/Val Activities

Post-launch Cal/Val activities at the Lake Tahoe Site will include installing an array of approximately 20 pressure transducers spaced around the lake shoreline (15 in lake, 5 atmospheric). These transducers may come from other Cal/Val sites that had been studied during the 1-day Fast Repeat Orbit. Deployment of the transducers will help to supplement existing *in situ* stage recorders to determine water surface variations across the surface of the lake. If water surface slopes are determined to be significant, two-days of boat-measured transects recording water surface elevations across the lake will be performed to correspond with overflights by SWOT.

7.2.2.3 Prairie Potholes Small Lakes Cal/Val Site (U.S. Project Site)

7.2.2.3.1 Site Description

The Pairie Potholes Small Lakes Cal/Val Site is located near Jamestown, North Dakota, USA (Figure 65). The site is typical of the Prairie Potholes Region, a post-glacial landscape stretching from Iowa to Alberta, Canada, that is composed of numerous small waterbodies, ranging from several tens of square meters up to several kilometers in surface area. Some of the smaller waterbodies are ephemeral and go dry during the early fall, but most of the larger waterbodies are perennial and have dynamic (1+ m) changes in water-surface elevations. In addition, the Prairie Pothole Cal/Val Site is affected by ice, snow, and rain, making it a good location for also testing the performance of SWOT flagged data products. The Prairie Potholes Validation Site is the location of a multi-decadal study funded by US EPA and USGS investigating water dynamics in this region.

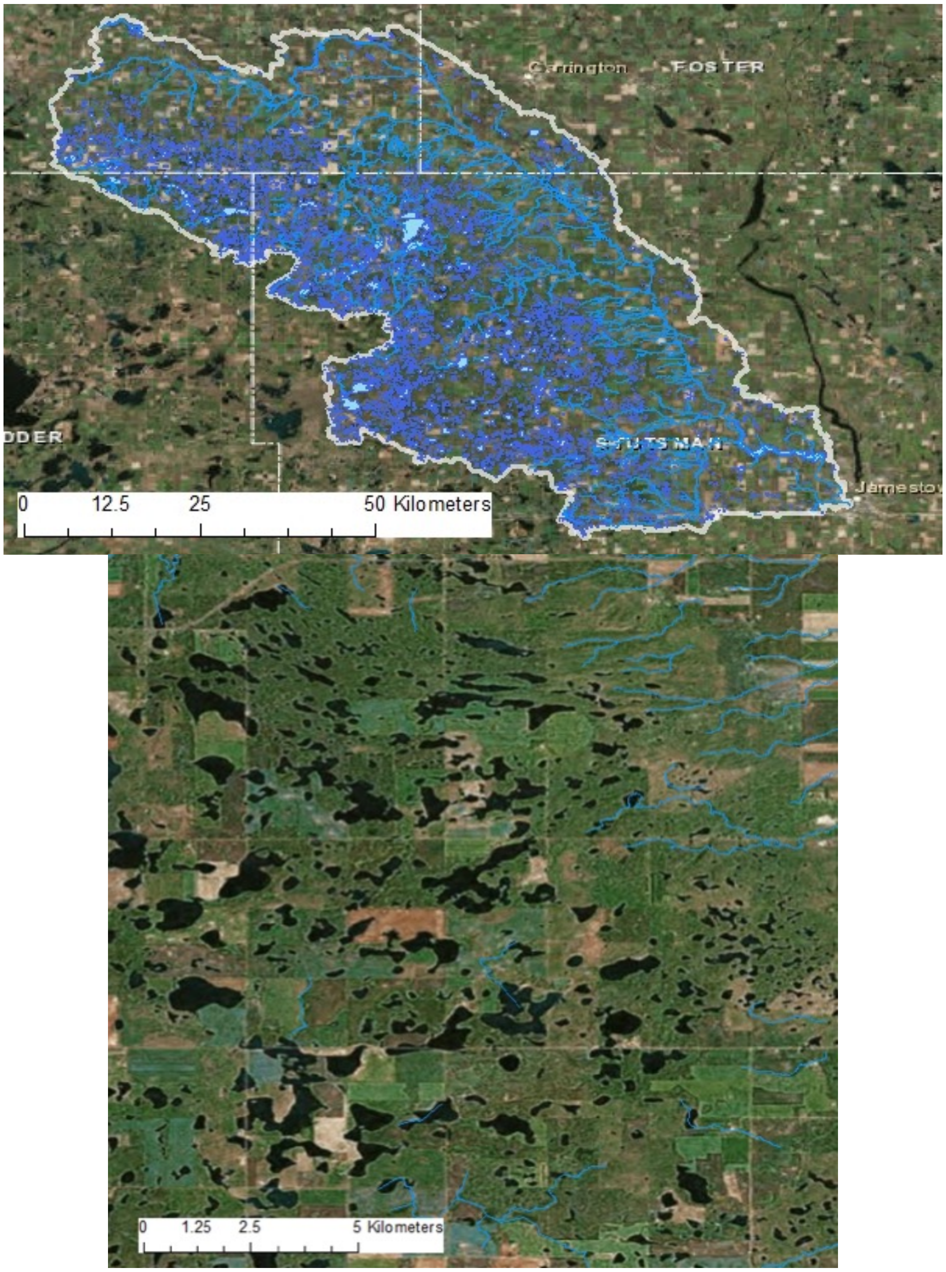


Figure 65. Map of the Prairie Potholes Validation Site, near Jamestown, North Dakota, USA. Second panel shows a close-up of the numerous small waterbodies typical of the region.

7.2.2.3.2 Site Goals

The goals of the Prairie Potholes Validation Site are to validate SWOT measurements of surface-water height and inundated area for small waterbodies, some of which are ephemeral.

7.2.2.3.3 Site Instrumentation

Aerial lidar was flown in 2010-2012 and high-resolution DEMs are available for the site. It is unknown if the aerial lidar was flown when the potholes had low water levels. There is one existing stream gage in the upper watershed and one in the lower watershed, both are operated by USGS. There are historical datasets of surface water changes in several of the larger waterbodies and each year approximately five to ten pressure transducers are deployed in waterbodies to record their dynamics. In addition, the watershed of the Cal/Val site has several calibrated coupled surface- and ground-water numerical models at various resolutions from medium to fine, with all the models available from the USGS and US EPA.

7.2.2.3.4 Pre-launch Site Characterization

There are three primary pre-launch activities that are proposed for the Prairie Potholes region: 1.) A study to understand wind setup on small lakes (proposed for 2017); 2.) A study to determine accuracy of derived inundation extent from the intersection of lidar dems with water level (proposed for 2017); 3.) A study to evaluate accuracy of inundation extent validation methods in low-elevation, non-wetland environments using AirSWOT (proposed for 2017, will require 2-days of AirSWOT flights).

For these pre-launch activities proposed for 2017, approximately 40-60 pressure transducers will be installed to measure water-surface elevations (~50 in small lakes, ~10 for atmospheric corrections). Wind setup will be evaluated using the pressure transducer network, as well as deployment of ten weather stations that are to be purchased for Cal/Val uses. Lidar DEMs already exist for the site, but approximately two weeks of field work will be needed to validate inundation extent using the field methods proposed earlier (Section 6.4.3.2), and will be synchronized with two-days of concurrent AirSWOT overflights. A short 2-3 day field visit will be required to remove the pressure transducers at the end of the deployment period. There will need to be approximately three months of staff time set aside to evaluate and compare all the various data components.

7.2.2.3.5 Post-launch Cal/Val Activities

The Prairie Potholes Cal/Val site is not located under the SWOT 1-day fast repeat cycle, as such, post-launch Cal/Val activities primarily will occur during the science orbit portion of the mission. The post-launch Cal/Val activities at the Prairie Potholes Cal/Val site will rely primarily on the installation of approximately 30 pressure transducers (~25 in small lakes, ~5 for atmospheric correction). Depending on the time of year of the launch of SWOT and the likelihood of ice cover, the installation of pressure transducers at this site will occur either pre-launch or during the 1-day fast orbit. A short 1-2 day field visit will be required to remove the pressure transducers and approximately two weeks of staff time will be required to work up the data and compare it to SWOT data products.

7.2.2.4 Yukon Flats Lake & Wetland Validation Site (US Project Site)

See section 8.2.3.2 for full description

7.2.2.5 Sierra Nevada Alpine Small Lakes Validation Site (US Project Site)

7.2.2.5.1 Site Description

The Sierra Nevada Alpine Small Lakes Validation Site (SNASL), is located in the Sierra Nevada Mountains of California, approximately 50 km south of Lake Tahoe (Figure 66). This site was chosen to help isolate the wet troposphere component of the error budget due to the relatively low amount of wet troposphere compared to more lowland sites. In addition, high-elevation lakes provide an important source of water for many human populations and understanding the errors associated with these environments will contribute to SWOTs utility.

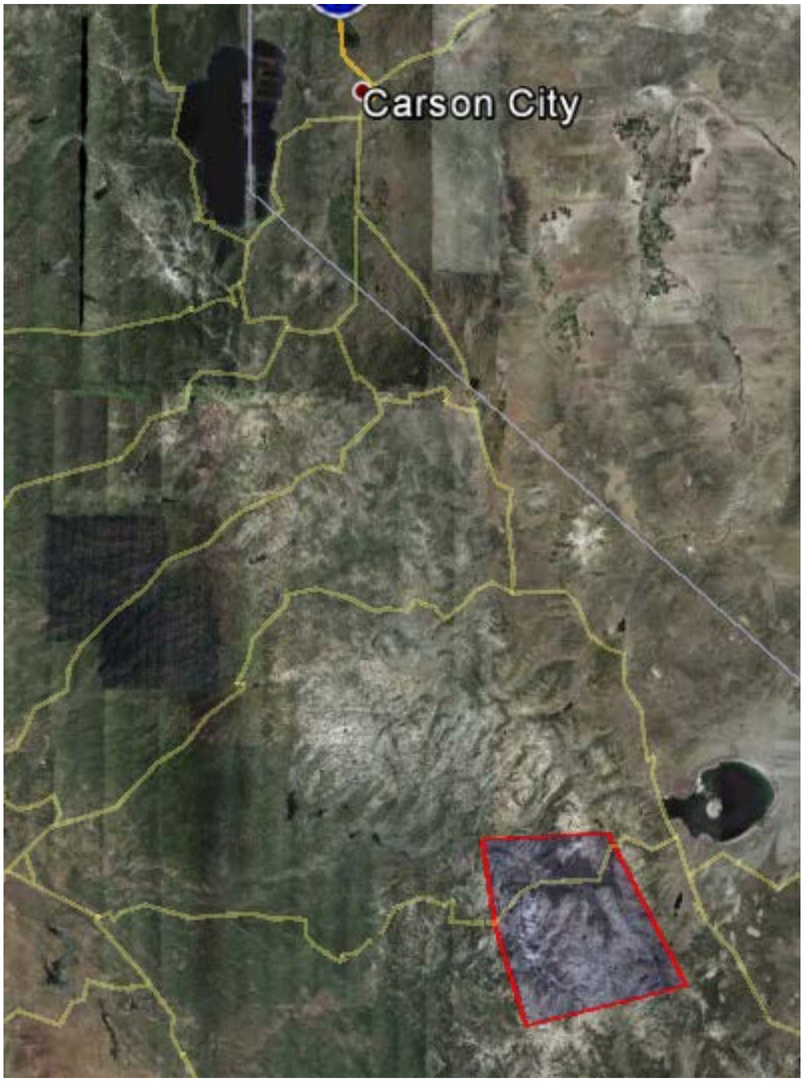


Figure 66. Map of the Sierra Nevada small lakes Cal/Val site, with Lake Tahoe to the north, and Mono Lake to the East.

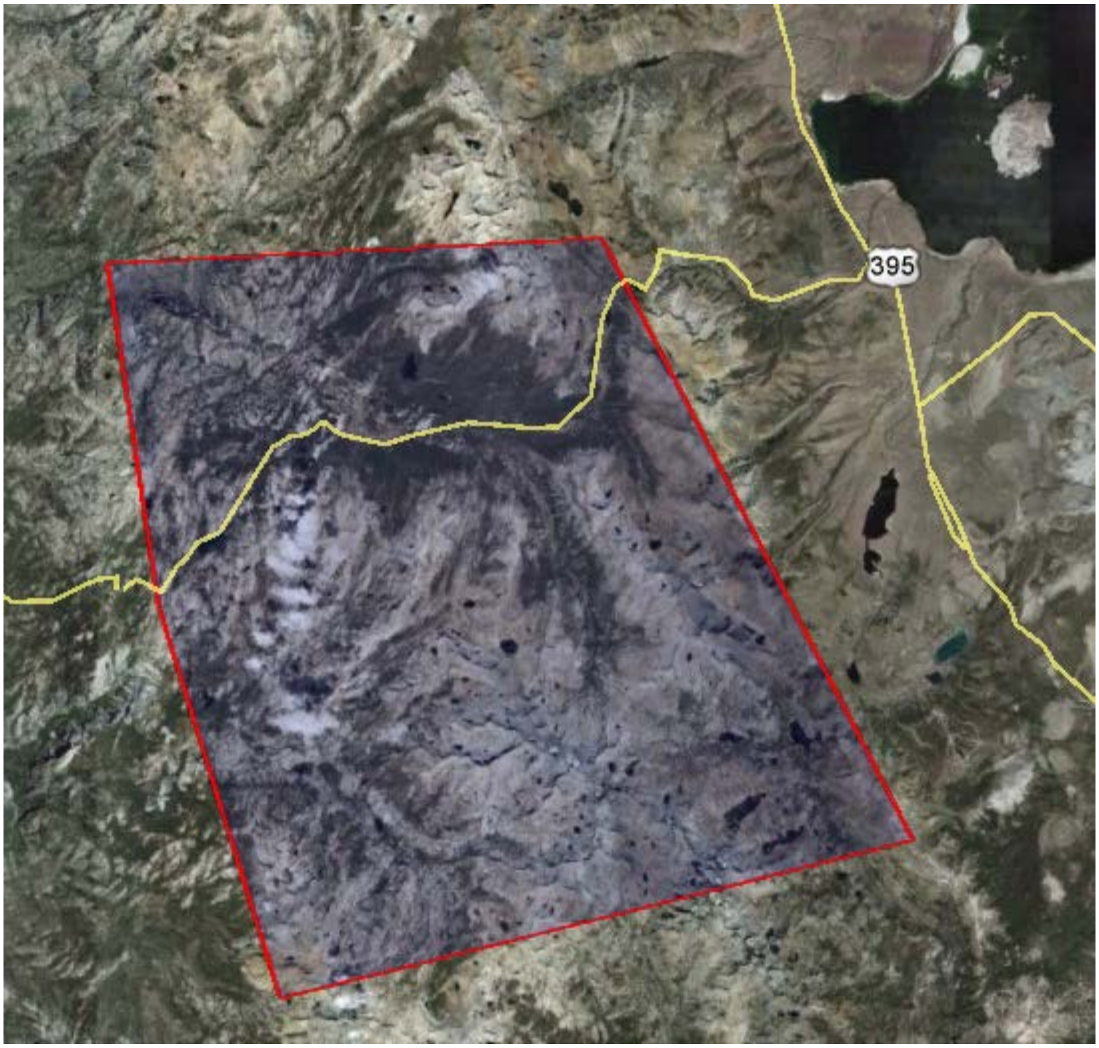


Figure 67. Close up of Sierra Nevada small lakes Cal/Val site. There are approximately 80 small lakes in the enclosed area, many with relatively good road access, and the site is primarily in Yosemite National Park, which is interested in studying these lakes.

7.2.2.5.2 Site Goals

The goals for this Cal/Val site are to understand SWOT dynamics for small high-altitude mountainous lakes. These lakes are of primary interest because they have a very low wet troposphere component and are important contributors to the water supply for human populations.

7.2.2.5.3 Site Instrumentation

At present, there is no existing instrumentation at these sites.

7.2.2.5.4 Pre-launch Site Characterization

The Sierra Nevada small lakes Cal/Val site is outside the SWOT 1-day fast repeat orbit, as such, pre-launch site characterization will be minimal. Permissions to install pressure transducers and site identification will require approximately two weeks of staff time.

7.2.2.5.5 Post-launch Cal/Val Activities

Post-launch Cal/Val activities include installing pressure transducers with GNSS-survey level accuracy, most likely in the period immediately after the 1-day fast orbit. Site characterization will consist of installing approximately 30 pressure transducers (~25 small lake sites, ~5 atmospheric sensors), primarily in the region covered by aerial lidar, just southwest of Mono Lake (Figure XX). A team of two field members will need approximately one week to install the pressure transducers, and approximately one week to remove them. Approximately one-two weeks staff time will be needed for data processing of the GNSS data as the static collections are more complex than RTK collections at other Cal/Val sites.

7.2.2.6 South American Validation Sites: Andean Lakes (France & Foreign Partner Sites)

7.2.2.6.1 Site Description

In south Chile there is a set of few lakes for which daily gage heights are available from *Dirección General de Aguas* (DGA) through a system of public request (www.dga.cl). The Lakes in situ data have to be leveled using GPS positioning and will then be available for real time validation of water height from SWOT.

These data have already been used to validate the SARAL/Altika data and compare with Envisat products.

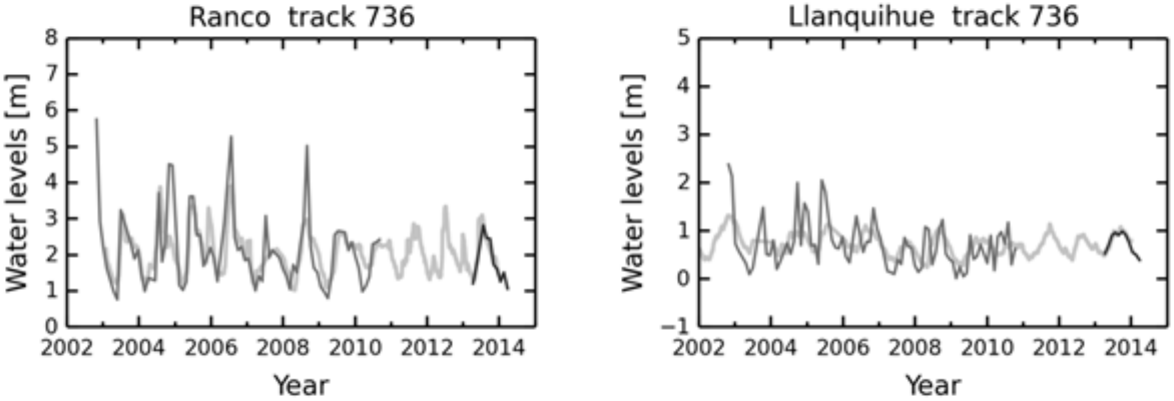


Figure 68. Examples of In Situ water level for Lake Ranco and Llanquihue compared to Envisat and SARAL/AltiKa measurements.

Moreover, following a first campaign done in 2005 over 3 of the lakes of the regions named "*los lagos*" near the city of Puerto Mont, some additional leveling of the lake surface using kinematic GPS measurements will be performed in cooperation with the university of Concepcion: under the framework of the South American Group of SWOT early adopters.

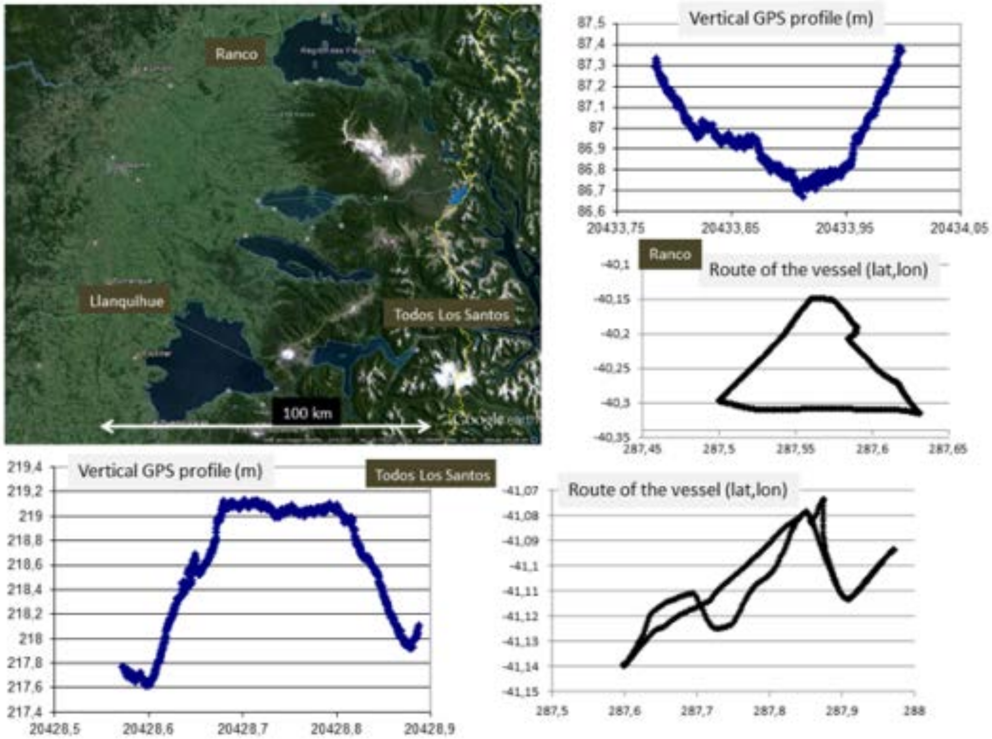


Figure 69. Map of the Los Lagos and some preliminary vertical profiles along the lakes Ranco and Todos de los Santos.

7.2.2.6.2 Site Goals

- In situ validation of water height measurements from SWOT for lakes in mountain area.
- Validation of slope accuracy using vertical GPS profile over the lake

The topography of the surrounding of the lakes of the *Los Lagos* region will allow testing layover effect (mountains and volcanoes are present as well as forests along the shore) but these lakes are also large enough to present some non-negligible geoid variations (see Figure 69). Some small islands and very complex shoreline delineation (especially for the Todos de los Santos) may be a good target for classification validation.

7.2.2.6.3 Site Instrumentation

These lakes are equipped with in situ gauges delivering daily data without any restrictions.

The region is easily accessible and all lakes are connected by roads

7.2.2.6.4 Pre-launch Site Characterization

-Delineating the lake’s shorelines from GPS survey could be done prior to the launch.

-Field work with kinematic GPS in order to determine geoid slope over the lakes Ranco, Llanquihue and Todos de Los Santos. There is a need to repeat this leveling at different periods in order to check the potential seiche effects.

-check availability of meteo station (anemometer in particular) for determination of potential seiches over the selected lakes

-GPS leveling of the in situ gauges (in coordination between university of Concepcion and DGA

7.2.2.6.5 Post-launch Cal/Val Activities

- regular GPS leveling of the gauges
- use the Near Real Time in situ data for validation of water level measured by SWOT
- use the vertical profile for validation of slope and calibration of roll/phase error.

7.2.3 Wetland Validation Sites

7.2.3.1 Lower Mississippi River Wetland Cal/Val Site (U.S. Project Site)

7.2.3.1.1 Site Description

The Lower Mississippi River Wetland Cal/Val site is located in Southern Louisiana (Figure 70). The site has a range of different waterbodies with varying degrees of inundation and vegetation cover, which will be used to test SWOT performance for measuring water-surface elevation and inundation extent in water bodies under a variety of vegetation types. A key component of the Lower Mississippi River Wetland Cal/Val site is the extensive existing gage network, the Coastwide Regional Monitoring System (CRMS). The CRMS network consists of nearly four hundred stations at which measurements of water-level elevation, vegetation classes, percent vegetation cover and other parameters are measured (http://pubs.usgs.gov/fs/2010/3018/pdf/FS2010-3018.pdf). Data can be accessed easily online at the CRMS data website (http://lacoast.gov/crms2/home.aspx).

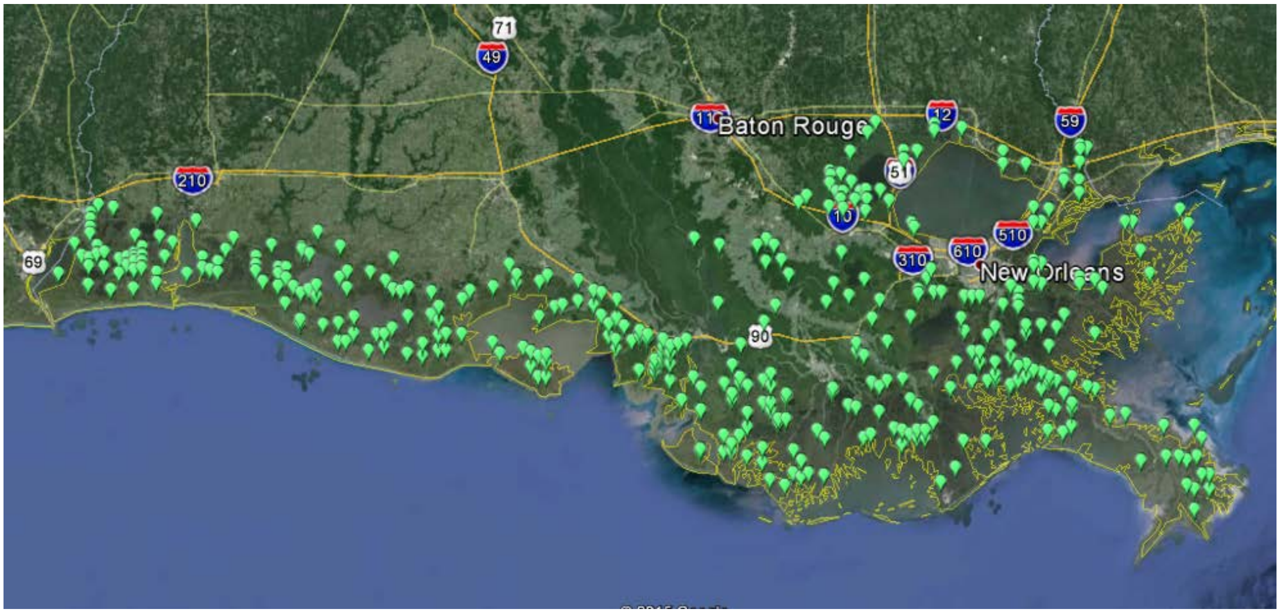


Figure 70. Map of the Lower Mississippi Wetland Cal/Val site. The Coastwide Regional Monitoring System (CRMS) gages are shown in green.

7.2.3.1.2 Site Goals

The goal of the Lower Mississippi Wetland Cal/Val site is to:

1. Validate the ability of SWOT measurements to accurately characterize and measure water presence under a range of vegetation types, from high-canopy cover to emergent vegetation to mixed open water.
2. Validate the ability of SWOT measurements to accurately characterize and measure water-surface elevation and inundation extent over a range of vegetation types in water bodies, including ephemeral and fluctuating water levels.

7.2.3.1.3 Site Instrumentation

The Lower Mississippi Wetland Cal/Val site has a large number of existing gages that should suffice for SWOT and AirSWOT comparisons but if any additional stage measurements are required, project pressure transducers will be deployed. In addition, the survey quality of the water-levels of the existing gages will be verified. One or more weather stations, potentially including stations installed within the vegetation would be useful to help control for vegetation motion from wind and waves on the underlying water surface. Flights of AirSWOT with KaSPAR and a near-infrared camera would be recommended.

7.2.3.1.4 Pre-launch Site Characterization

The wetland site will need to have aerial lidar data available to characterize the topography and the vegetation heights, with the data collection preferably collected as close to SWOT launch as possible. There are several existing lidar datasets, with significant overlap between years and with some relatively recent (2013, 2015), suggesting that this site is of sufficient interest to require repeat lidar flights. If a recent lidar flight is not available within a year pre-SWOT launch, a lidar data collection flight would be recommended. More recent aerial lidar data will be preferred to sites with older data because the vegetation may have changed significantly since the lidar was flown.

Aerial lidar data will be used to segment the study site into classes of vegetation (based on height, canopy structure, and density) as well as inundation depth determined from field measurements. Field measurements that will be helpful characterize the Cal/Val wetland site include installation of pressure transducers in water bodies within a range of different vegetation types, as well as weather stations to help parameterize effects of vegetation motion and waves on SWOT measurements and data products. AirSWOT flights over the chosen wetland site in the pre-launch period have been performed but additional flights, if needed, would be recommended to help develop and test SWOT products for water-surface elevation and inundation extent under vegetation canopies.

7.2.3.1.5 Post-launch Cal/Val Activities

All of the chosen potential wetland Cal/Val sites are within the SWOT 1-day fast orbit path. As such, initial SWOT products, such as inundation extent and water-surface elevation, will be validated from the wetland Cal/Val site. The post-launch characterization will consist of the installation of 20 or more temporary pressure transducers in water bodies underlying a range of vegetation types. Installation of weather stations may be necessary if they are found to be helpful in the pre-launch testing. AirSWOT underflights, with KaSPAR and near-infrared camera measurements, coincident with SWOT passes will be useful for validating the SWOT measurements of water-surface elevation and inundation extent.

7.2.3.2 Yukon Flats Lake & Wetland Validation Site (US Project Site)

7.2.3.2.1 Site Description

The Yukon Flats is a large, tectonically-controlled basin in Central Alaska, approximately 150 km north of Fairbanks. The Yukon River flows through the heart of the basin, and wetlands and thousands of small lakes dominate the surrounding areas. These lakes and wetlands are characteristic of similar features found at northern high latitudes, including West Siberian Lowlands, portions of Eastern Siberia, and lowland areas in Northern Canada. As such, validation of SWOT's ability to detect lake water surface elevation, inundation extent and storage change, as well as the ability to detect height and inundation extent in boreal vegetated areas. The Yukon Flats received extensive study via ground-based and AirSWOT measurements during summer 2015. As such, it is already comparatively well-characterized relative to some other SWOT validation sites.

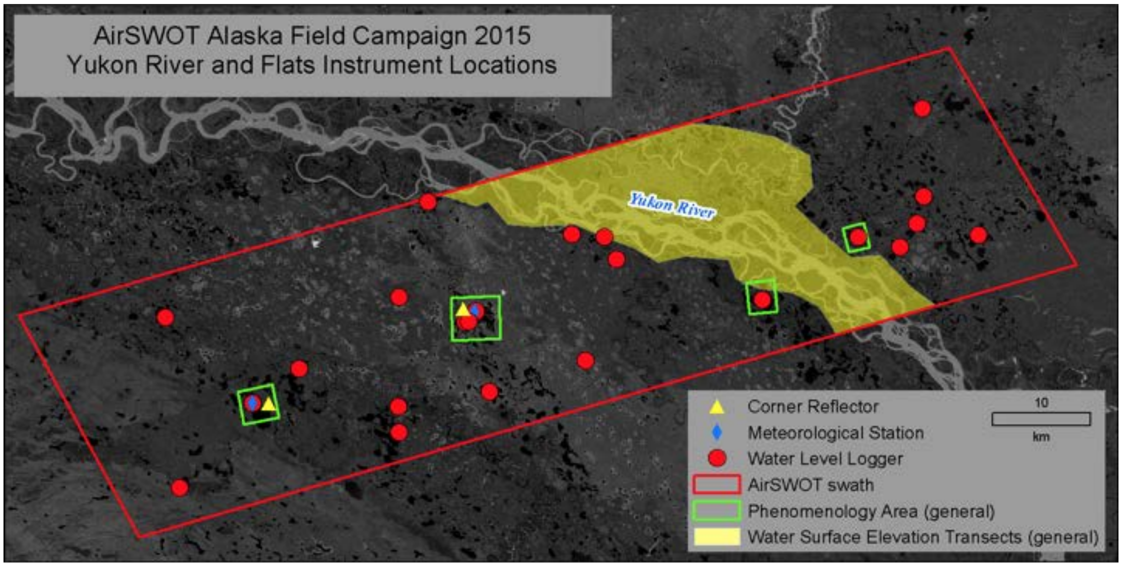


Figure 71. The Yukon Flats Field Site

7.2.3.2.2 Site Goals

The primary goals of the Yukon Flats validation site are to:

5. Validate measurements of water surface elevation, inundation extent, and water storage in small wetland lakes. These lakes occur frequently across boreal regions and will be key targets for SWOT, and the Yukon Flats is a highly representative example.
6. Understand the ability of SWOT to measure wetland inundation under boreal vegetation.
7. Although it is not a primary goal, this site will also include at least one large Arctic River (the Yukon), as well as multiple smaller tributaries. These could be used to validate SWOT-derived height and slope if appropriate field data were collected.

7.2.3.2.3 Site Instrumentation

The Yukon Flats study area is not well-instrumented. The only permanent stream gauge in the region is on the Yukon River at the Dalton Highway bridge (listed as the Yukon River at Stevens Village), substantially downstream of the Yukon Flats. Much of the Flats is located within the Yukon Flats National Wildlife Refuge, and the refuge staff have installed temporary gauges in a number of lakes in the past. Similarly, a research team from the USGS led by Michelle Walvoord and Rob Striegl has collected extensive hydrologic and biogeochemical measurements in the Yukon Flats in the past. A portion of the flats was flown with lidar in 2010, but the remainder of the area is not yet covered by a high-resolution DEM. In addition, a team led by Tamlin Pavelsky conducted extensive fieldwork in the Flats during summers 2015 and 2017. Water level time series were successfully measured in 13 lakes, data characterizing vegetation, wind speed, inundation extent were collected, and multiple AirSWOT data collections occurred. One, on June 15th, occurred during clear-sky conditions and thus produced simultaneous radar and optical images of the region.

7.2.3.2.4 Pre-launch Site Characterization

A significant degree of site characterization has already occurred during the summer 2015 field season, including collection of multitemporal AirSWOT radar data, AirSWOT optical data, and field measurements of water surface elevation, wind speed, water/land boundaries, and vegetation characteristics. However, the lack of a suitable high-resolution DEM points to the need for additional work prelaunch. As such, we recommend collection of a high-resolution LiDAR DEM over at least a portion of the study area prior to launch. Unlike other types of DEM, this data will provide information on both vegetation height and bare earth elevation. This combination will prove useful in characterizing the ability of SWOT to observe water under vegetation and will also help to characterize vegetation-induced layover in northern wetland environments.

7.2.3.2.5 Post-launch Cal/Val Activities

Cal/Val activities after launch will focus on the first summer post-launch. In the Yukon Flats, pressure transducers will be installed in lakes to measure variations in water surface elevation and inundation extent. Lakes will be selected to cover a range of sizes spanning the lower bounds of SWOT detectability, from ~1 ha to >5 km². Near-infrared aerial photography will be collected coincident with SWOT overflights to validate detection of inundation extent. In addition, the Yukon Flats will serve as the primary validation site for SWOT detection of inundation under boreal vegetation. Point measurements of water surface elevation, vegetation characteristics, and inundation extent will be made using ground-based surveys.

In addition to these basic measurements, two additional sets of measurements would provide desirable validation capabilities. AirSWOT measurements would provide full, 2-D validation of SWOT water surface elevations in Yukon Flats lakes and wetlands and would help with interpretation of SWOT water classification, as AirSWOT will provide similar data at much higher spatial resolution. In addition, airborne L-band SAR (e.g. UAVSAR) would provide robust measurements of water surface extent under vegetation in the Yukon Flats, which would offer a substantial improvement over ground-based surveys.

A portion of the Yukon Flats is included in the 1-day repeat orbit (Figure 72). If this orbit is available during the open-water seasons, it would be highly valuable to conduct a field campaign during during this time period, as the hydrology of northern basins like the Yukon tends to evolve rapidly during and immediately after the spring breakup of river ice.

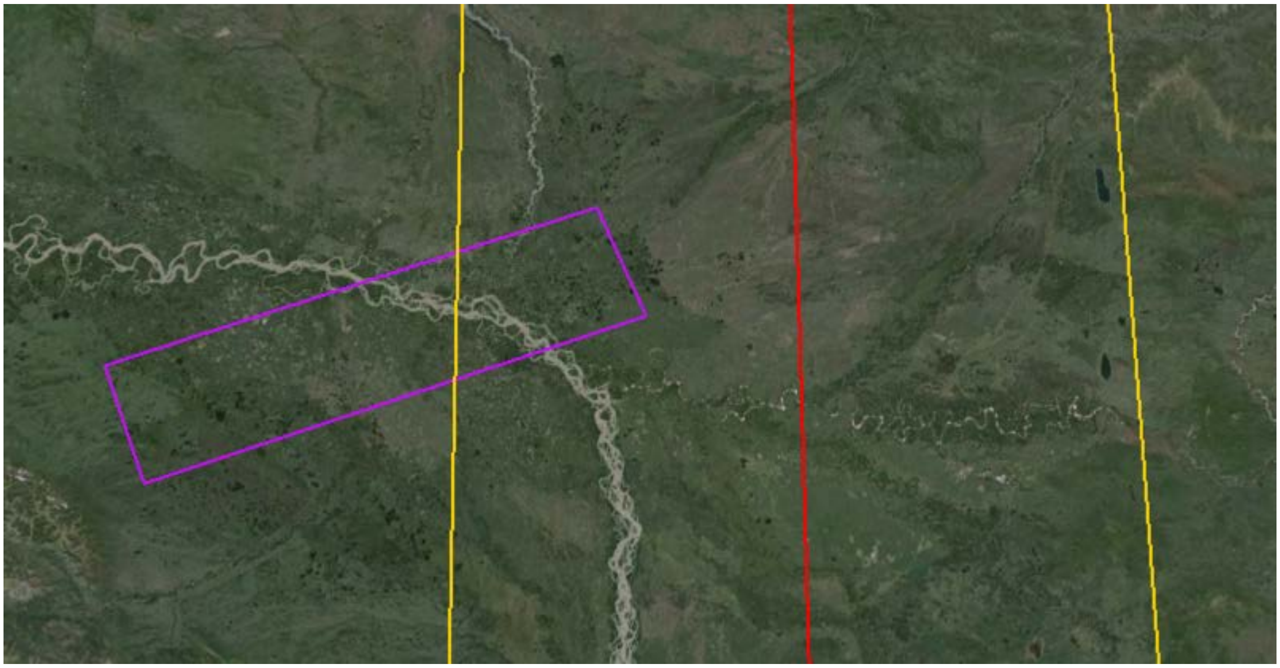


Figure 72. The Yukon Flats Field Site & the one day repeat orbit.

7.2.3.3 Everglades Wetland Validation Site (US Project Site)

7.2.3.3.1 Site Description

The Everglades Wetland Validation site is located in Southern Florida, USA, 75 km west of Fort Lauderdale (Figure 73). Commonly referred to as the "River of Grass", the Everglades are a series of dynamic wetlands and water bodies that have significant variations in water-surface elevations, both intra- and inter-annually, with complex wetland water surfaces due to variations in vegetation and topography. One of the primary benefits of using the Everglades as a validation site is the large amount of available data, models, and science reports (over 800 at last count in 2014). Much of this science work has been funded through the multi-decadal, mutli-billion dollar Comprehensive Everglades Restoration Plan (CERP), supported by the U.S. Army Corps of Engineers and the USGS Greater Everglades Priority Ecosystems Science Program. Funding for CERP and science in the Everglades is expected to continue for decades to come. In addition, the Everglades contains Everglades National Park, Big Cypress National Preserve, and the Everglades Long-Term Ecological Reference (LTER) site (http://fcelter.fiu.edu/), all of which have extensive ongoing research and data-collection programs as well as numerous researchers working throughout the region.

The hydrology of the Everglades is driven by rainfall, with an average rainfall of one and a half meters. A typical year consists of a relatively dry late fall, winter and early spring, followed by a wet summer, when the majority of rain occurs. Typical intra-annual stage variations are approximately one meter (Figure 74). During the high-water season, water spreads out over large areas, with a dense multitude of water bodies present, ranging from open water of one square kilometer, to expanses of wetland from several square meters in area up to several tens of kilometers. All of these water bodies change dynamically throughout the year and some go dry in the dry season. Vegetation consists primarily of varying densities of one- to three-meter high grass and some overstory tree canopy.

The selected location of the ~600 square-kilometer Everglades Validation site is outside the Everglades National Park boundaries to avoid possible issues with instrument installation and data collection, and far enough west to avoid potential air-traffic conflicts with the busy Miami-Dade and Fort Lauderdale airports. The site is outside the SWOT one-day fast repeat orbit, and as such, will be used as a validation site once the SWOT science orbit is achieved.

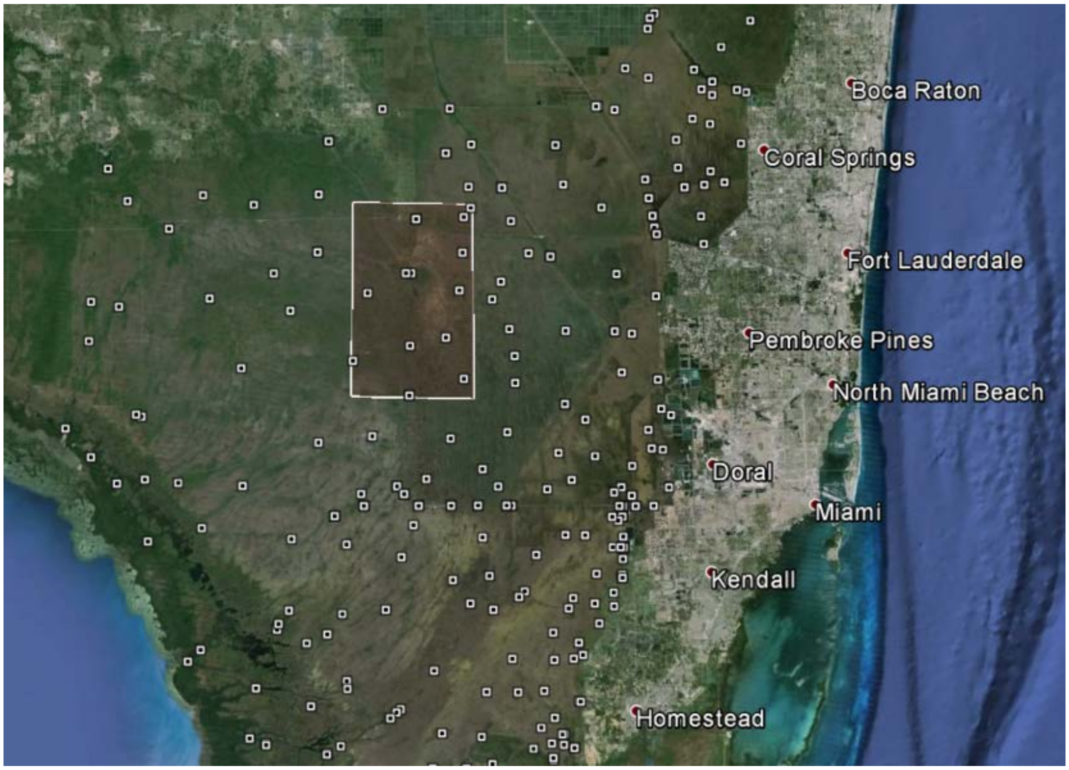


Figure 73. Location map of the Everglades Wetland Validation site, west of Fort Lauderdale, Florida, USA. The red polygon is the location of the Everglades Wetland Validation site, and the white squares are the location of EDEN stage gages.

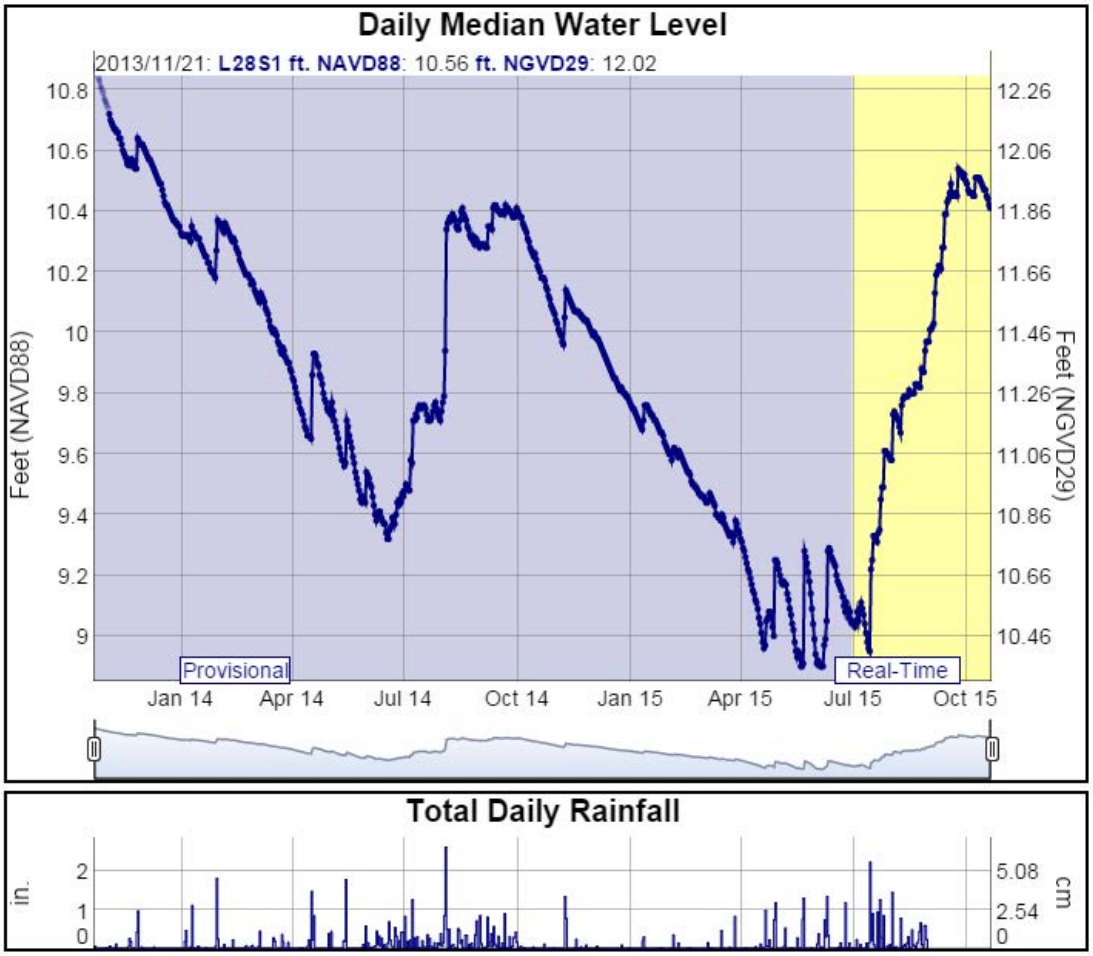


Figure 74. Plot of water stage level and rainfall from an EDEN real-time stage recorder, L28S1, for Water Years 2013-2015 (available at: http://sofia.usgs.gov/eden/eve/). This site is typical of most Everglades water bodies, with approximately one-meter of stage change throughout the year. This particular site is one of about a dozen located within the SWOT Everglades Wetland Validation site.

7.2.3.3.2 Site Goals

The goals of the Everglades Wetland Validation site are to validate SWOT rain-flagging, and SWOT measurements of water-surface elevations and inundated area, particularly under a mixed moderate-height vegetative canopy typical of lowland wetlands.

7.2.3.3.3 Site Instrumentation

The Everglades have an extensive and ongoing data collection network for water-surface elevations and meteorological conditions, as well as high-resolution topographic DEMs, near-real time water-surface generation, and a wealth of additional datasets that have been compiled. Much of this data is available through the South Florida Information Access system (SOFIA; http://sofia.usgs.gov/). A key component of the CERP and of particular use for SWOT Cal/Val purposes is the Everglades Depth Estimation Network (EDEN; http://sofia.usgs.gov/eden/), a series of approximately 300 stage gages located throughout the Everglades, with the majority of the stage gages surveyed to high-quality GNSS accuracy and reporting in real-time.

For rainfall and meteorologic conditions in the Everglades, there are approximately two-hundred real-time meteorologic stations available from the South Florida Water Management District and 81 non-real time rainfall gages, as well as 15-minute NEXRAD coverage from the U.S. National Weather Service. A 2 km x 2 km gridded, 15-min rainfall data product is created by locally-correcting the NEXRAD data with the dense meteorologic station network (available through http://sofia.usgs.gov/eden/eve/).

7.2.3.3.4 Pre-launch Site Characterization

Pre-launch activities for the Everglades Wetland Validation site include establishing connections with USGS and other researchers working in the area as well as developing an understanding the potential errors or biases in the existing data collection network (e.g. how accurate NEXRAD-derived rainfall estimates might be, and the accuracy of water stage elevations from the EDEN network). Because this Validation site is not within the SWOT one-day fast repeat orbit, most of the field activities will occur post launch, though most of the data used to validate SWOT will rely on the existing data collection network.

7.2.3.3.5 Post-launch Cal/Val Activities

Post-launch activities for the Everglades Wetland Validation site include a potential aerial lidar flight to help characterize vegetation and create a high-quality DEM, if these data are not available or the site has not been flown with lidar previously through the USGS 3DEP program. Coordination with USGS researchers will include the coordination of a satellite or aerial photography data collection for inundated area extent (e.g. near IR imagery), coincident with SWOT overflights. The existing EDEN gage network should be sufficient for comparison to SWOT water-surface elevation and the NEXRAD-derived rainfall estimates should be sufficient for SWOT rain-flagging, though the uncertainties of these networks should be well understood pre-launch.

7.2.4 Tidal/Estuarine Validation Sites

7.2.4.1 Severn Estuary and River Validation Site (UK Project Site)

7.2.4.1.1 Site Description

The Severn River Cal/Val site is located in the South-West of the UK., downstream of the town of Gloucester (Figure 75) which is the upstream tidal limit. The river in this 90-km study reach is estuarine with a huge tidal range (~14m, the 2nd or 3rd highest in the world) and extensive tidal flats. It is a single-threaded low energy meandering channel carrying a moderate sediment load and experiences some evolution of the bed and banks. The reach varies in width between ~100m at the upper end (approximately 5km below Gloucester) to 24km at the lower limit of the SWOT fast sampling orbit swath (see figures below)

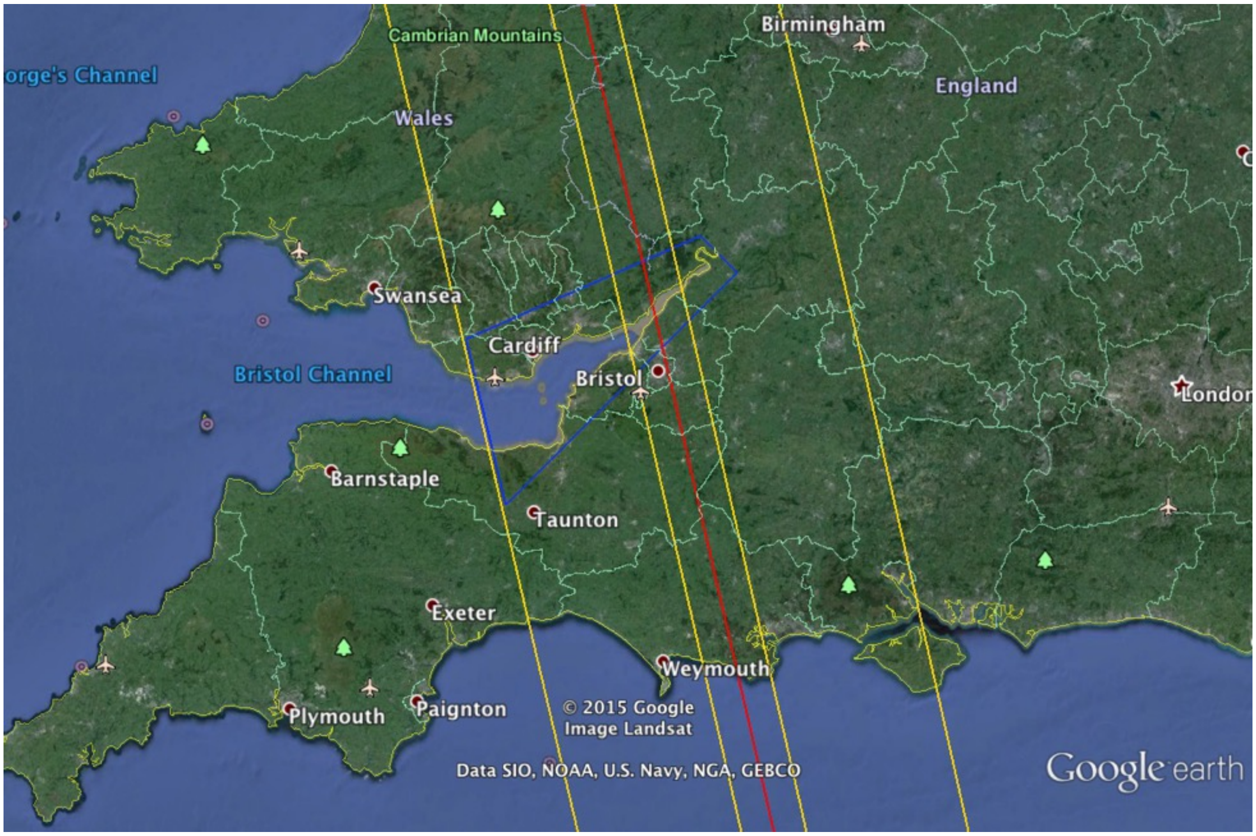


Figure 75. River Severn study site (blue polygon) covering the area from the seaward limit of the SWOT fast sampling orbit swath upstream to where the channel width decreases below ~100m.

Figure 76. Zoom of River Severn study site (blue polygon).

The reach experiences significant river flow inputs (low flow ~30-50 m^3s^{-1}, flood flows up to ~1000 m^3s^{-1}), which are only marginally regulated. The tidal prism is massive, and is sufficient to form a bore up to ~2m high during spring tides. There are extensive mud flats, which are inundated at high tide. River flood flows can occur at any time of the year, but are more common in the winter, and significant storm surges (up to 2m of skew surge) can also occur as low pressure systems track over the area. The estuary has also been the proposed site of a large tidal barrage designed to harvest renewable energy with a maximum potential output of approximately 7% of the UK's energy needs.

The River Severn has not been the focus of SWOT-related studies to date, largely as a result of the UK's relatively late entry to the Mission. However, it is the only major eastuary that will be sampled during the SWOT fast sampling phase and it is therefore an essential Cal/Val and science site for the mission. The River Severn Cal/Val study site will therefore be used to validate SWOT's ability to detect water-surface elevation, slope, inundation extent, and discharge in a highly dynamic tidal estuary.

7.2.4.1.2 Site Goals

There is one primary validation goal for the River Severn Cal/Val site:

8. Validate SWOT's ability to measure and characterize dynamic tidal estuaries. Characteristics to be studied include water-surface elevation, slope, inundation extent, and discharge.

7.2.4.1.3 Site Instrumentation

A lidar survey of some parts of the shoreline exist, but this will need to be updated with a new and spatially complete survey taken at low water in the period prior to the SWOT launch. This will need to be supplemented with a high water bathymetric survey using side scan sonar and the two surveys merged into a seamless DEM product.

Tide gauges maintained by the UK National Tide and Sea Level Facility exist at Avonmouth in the middle of the study domain and at Hinckley Point just beyond the seaward limit. The normal tidal limit is at Gloucester where a weir prevents the further upstream propagation of the tide. Several river gauging stations exist at Gloucester and above. The storm surge climate is relatively well characterized by the tide gauges, but the quality of the river gauges will need to be assessed and if necessary rating curves will need to be revised (or detailed 2D hydrodynamic models constructed for the gauge sites to extrapolate the rating curves).

One of the primary pre-launch needs for the River Severn Cal/Val site is a calibrated 2D hydraulic model (e.g. TELEMAC) to be able to test SWOT data products in both the pre- and post-launch periods. s

7.2.4.1.4 Pre-launch Site Characterization

The following tasks will need to be undertaken pre-launch:

- Installation of a dense network of geodetically leveled pressure transducers every 1-2km along the reach, including on both banks where the channel becomes wide enough for significant cross-channel elevation differences to form.
- GPS boat surveys of water surface elevation to determine long profile water slopes (and particularly slope curvature) at different tidal states.
- Quality assessment and, if necessary, revision of discharge rating curves for river gauging sites.
- ADCP measurements of discharge and velocity at approximately ~10 cross sections along the reach profile.
- Low water lidar and high water side scan sonar surveys.
- Air photo survey.
- Development, calibration and validation of a 2D model of the site.

These are necessary to both gain insights into processes at the site, but also to test and refine safe sampling procedures in such a highly dynamic, and therefore dangerous, environment.

7.2.4.1.5 Post-launch Cal/Val Activities

During the 1-day fast repeat cycle the River Severn Cal/Val site will be the focus of intensive measurements to help validate SWOT measurements of water-surface elevation, slope, inundation extent and discharge. Field measurements will be similar to the techniques utilized in the pre-launch characterization phase, including boat-based measurements of water-surface elevation, slope, and discharge, as well as deployment of pressure transducers to measure temporal changes in water-surface elevation and slope. A number of sets of air photos will also be captured to validate SWOT measurements of inundation extent. Once developed, the 2D model will be used to diagnose and trouble-shoot any issues with the SWOT estimates for water-surface elevation, slope, inundation extent and discharge.

7.2.4.2 Connecticut River Tidal Cal/Val Site (US Project Site)

7.2.4.3 Site Description

The Connecticut River Tidal Cal/Val site extends from the USGS gaging station at Middle Haddam, CT, upstream to the USGS gaging station at Thompsonville, CT, USA (Figure 77). The river in this 65-km study reach is tidally-influenced, with a strong tidal influence on low- and moderate-flows extending through the middle of the reach near Hartford, CT. There is extensive existing gage infrastructure, including three mainstem (including one index-velocity gage at the downstream end) and four major tributary gaging sites operated by the USGS. All of the Cal/Val site is within the SWOT 1-day Fast Repeat Orbit though the river downstream of the Cal/Val site is under the 1-day fast repeat orbit's nadir location (e.g. not covered by KaRIN but covered by the altimeter). Though there are small flow regulation reservoirs in the upper watershed, the hydrograph of the river is typical of temperate rain- and snow-fall river systems, with distinct and large regular peaks and recession limbs from October to June and a low flow period in the summer from July to September. In addition, parts of the Connecticut freeze during the winter, with breakup occurring in March or April. A secondary reach of the Connecticut River upstream of Haddam, CT, serves as the Connecticut River Cal/Val site (no tidal influence) – see Sect. 7.2.1.4.

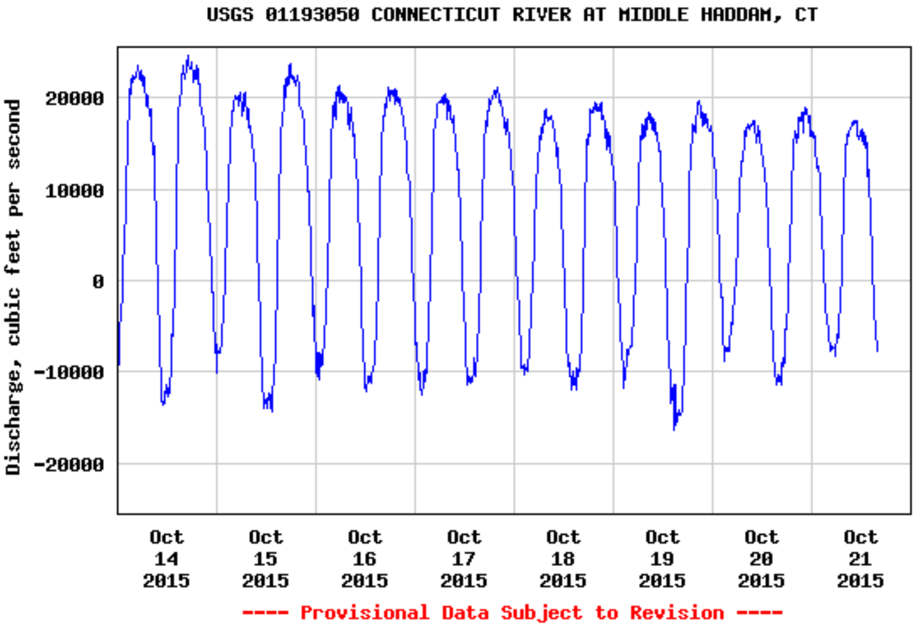
Figure 77. Map of the Connecticut River Tidal Cal/Val site, with the reach shown in red, the SWOT one-day fast repeat orbit swath extents of KaRIN shown by the yellow lines, the nadir altimeter shown with the red line, and USGS gages shown by the white encircled markers.

7.2.4.4 Site Goals

The goals of the Connecticut River Tidal Cal/Val are to validate SWOT's ability to measure or characterize water-surface elevation, slope, inundation extent, and discharge as well as validate SWOT's layover-, ice- and rain-flags. In addition to the Severn River, U.K., the tidal reach of the Connecticut River is the only tidally-influenced Cal/Val site and has a more moderate tidal action than does the Severn. As such, it will play an important role in validating SWOT measurements and data products for near-shore coastal areas.

7.2.4.5 Site Instrumentation

The Connecticut River Tidal Cal/Val site has three mainstem and four major tributary gaging sites operated by the USGS (Figure 77). Due to the strong tidal influence on discharge and stage, the lowest site, Connecticut River at Middle Haddam, is an Index Velocity gage station with a permanent side-looking ADVM (Figure 78). At Hartford, the river is still strongly tidal, and as such, the Hartford gage has a water height recorder only. The upper mainstem gage at Thompsonville, CT, uses a gage height recorder with rating curve to compute discharge and is entirely riverine dominated with no tidal influence. There are two gages downstream and outside of the Cal/Val site but these gages record gage height only and are within the nadir gap of the SWOT footprint during SWOT's one-day fast repeat orbit.



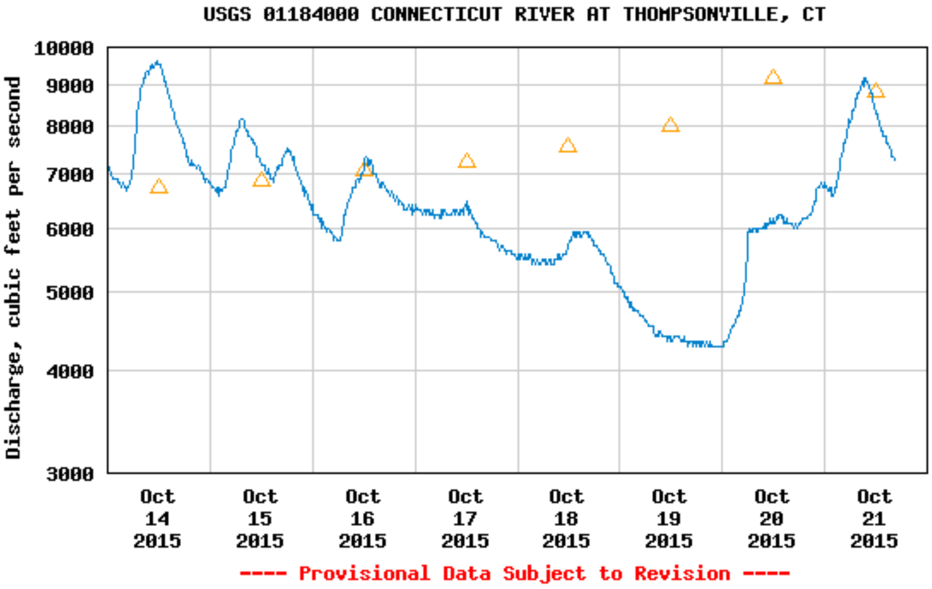


Figure 78. Differences in riverine and tidal discharge measurements for the Connecticut River Tidal Cal/Val site for October 14 - 21, 2015. The Connecticut River at Middle Haddam USGS gage is at the lowest boundary of the Cal/Val site and is strongly influenced by tidal effects (top panel); the Connecticut River at Thompsonville USGS gage has no tidal influence and is located at the upper boundary of the Cal/Val site (bottom panel).

There are two recent aerial lidar datasets covering the Connecticut River: one flown by NRCS in 2010 (available), and another flown in 2014 by USGS following Hurricane Sandy (in process). The 2014 aerial lidar currently is being processed and is not yet publicly available but it is expected to become available in 2016. There are several 1D and 2D models available for the Connecticut River, though the 2D models do not extend into the tidally-influenced reach.

7.2.4.6 Pre-launch Site Characterization

The pre-launch site characterization of the Connecticut River Tidal Cal/Val site include a short AirSWOT campaign consisting of two-days with multiple AirSWOT passes during various tidal stages scheduled for 2018. Concurrently, a ground campaign will have installed and levelled approximately 30 pressure transducers, as well as collecting day-of-flight longitudinal water-surface elevation and discharge measurements. If not performed previously, GNSS-leveling of the existing USGS gages will be required pre-launch. SWOT flagging will be evaluated using existing high-resolution lidar DEMs for layover flags, satellite-observations of ice and snow for ice flags, and local radar and weather stations for rain flags. In the months immediately preceding launch, approximately 30 pressure transducers will be installed for the one-day fast repeat orbit.

7.2.4.7 Post-launch Cal/Val Activities

The post-launch Cal/Val activities for the Connecticut River Tidal site include the installed pressure transducer measurements during the one-day fast repeat orbit, as well as two one-week campaigns for boat-based longitudinal water-surface elevation and discharge measurements.

7.2.5 Global Plan for Tier 2 Cal/Val Sites (U.S./France Joint Project)

The global network of numerous Tier 2 Cal/Val sites will build upon existing gaging station networks in member countries by converting existing stage recording data into high-accuracy real-world surface water elevations. For example, the USGS stream and lake gaging station network in the USA is freely available and easily accessible, and represents approximately 9,900 stations reporting stages and/or discharges at 15- to 60-minute intervals. The majority of these stations report stages with either low absolute elevation accuracies (e.g. +/- 5 m) though the relative variations in height will be much more accurate, or the reported stage is in an arbitrary elevation frame, not tied to real-world coordinates. To be able to use these sites for SWOT Cal/Val purposes, it would be most useful to have these station elevations tied into real-world coordinates, and that is the primary technique proposed here.

A typical Tier 2 Cal/Val site will consist of an existing stage and/or discharge gaging station, with hourly or more frequent data recording, combined with one high-accuracy GNSS measurement of the stage at a given time to convert the stage data into real-world water surface elevations. The Tier 2 Cal/Val sites have been broken into River and Lake sites in the sections below, though the infrastructure of the two are very similar. The advantage of the Tier 2 sites is having a large number of sites covering the full SWOT footprint swath and large area coverage across the continents to help with Cal/Val of SWOT measurements and data products. The disadvantage of these types of minimally-instrumented Tier 2 sites is that diagnosing errors from SWOT become more difficult than in Tier 1 sites. In addition, achieving a large fraction of global coverage will depend upon willing international cooperation.

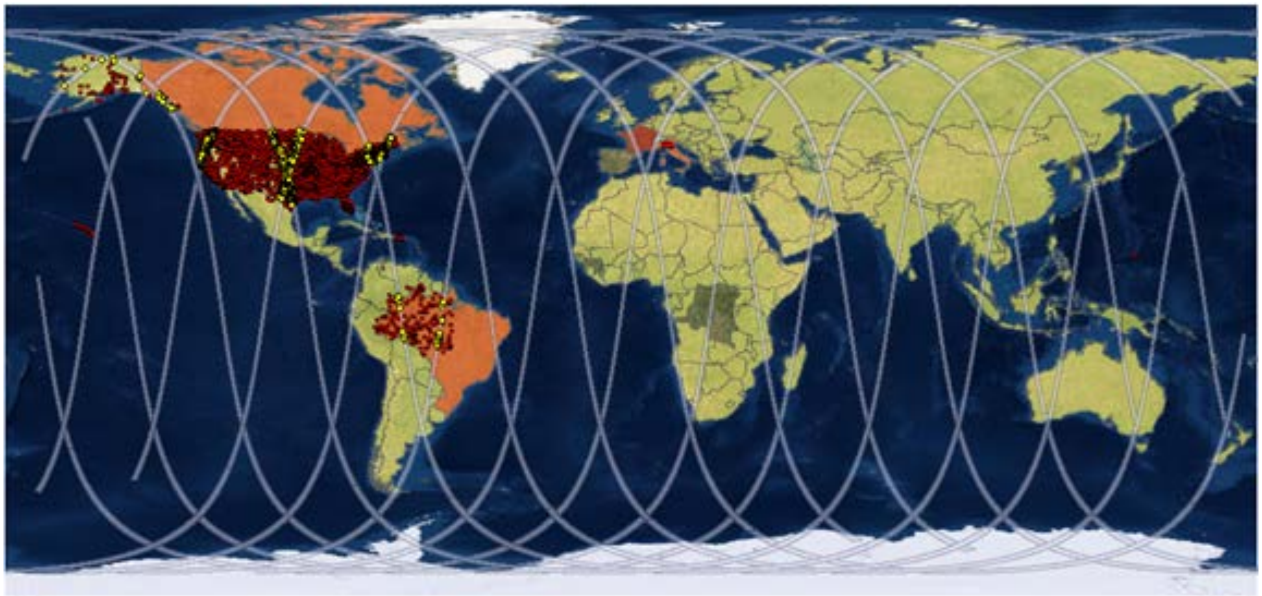


Figure 79. Map of potential global Tier 2 River and Lake Cal/Val sites. White lines show the SWOT one-day Fast Repeat Orbit. Countries shown in red are either SWOT project partners or unofficially-confirmed participants, countries shown in yellow are World Meteorological Organization members and are potential partners for Tier 2 sites. Already identified potential Tier 2 Cal/Val sites are shown by red dots (approximately 10,500 sites), with those sites under the SWOT one-day Fast Repeat Orbit shown in yellow (approximately 1,200 sites).

7.2.5.1 Tier 2 River Sites (U.S./France Joint Project)

7.2.5.1.1 Site Description

Each Tier 2 River Cal/Val site will include a stage recorder, which may or may not have an associated rating curve to compute discharge (though this is preferred). Each of these stage recorders will be surveyed to high-level GNSS accuracy, with survey-grade being possible in most cases, by either SWOT Team Members or by the host country representatives with the corresponding GNSS measurement being related to the stage recorder measurement spatially and temporally.

Establishing several hundred of these Tier 2 River Cal/Val sites with near global coverage would be an ideal situation. Realistically, however, a few hundred sites is more likely, though efforts have been started to initiate discussions with global meteorological organizations, such as the World Meteorological Organization, to help gain participation of countries interested in SWOT data. In addition, the USGS International Programs Office, which commonly interfaces on international water issues with the US Department of State, the International Monetary Fund, and the World Bank, has offered assistance in gaining access to the water representatives from host countries.

7.2.5.1.2 Site Goals

The goals of the Tier 2 River Cal/Val sites are to validate the absolute height, random height error, layover flagging, range drift, and roll/phase drift. Validation of some of these errors will be particularly important to evaluate when the measurements are far from the ocean, where calibration using the altimeter is not possible. In addition, for some of the Tier 2 sites located near meteorologic stations, it may be possible to evaluate wet-tropo delay errors and potentially the rain- and ice-flag data products.

7.2.5.1.3 Site Instrumentation

At each of the Tier 2 Cal/Val sites, it will be determined that the stage recorder is of sufficient accuracy for measuring water-surface elevations, such that the recorder meets or exceeds USGS gaging standards, and that the data are recorded at hourly or more frequent time intervals. In addition, sites with web- or real-time streaming data availability will be given preference, though in some countries, these types of gages are not used and data is recorded offline to be published later. There are some sites that will be given preference due to their location under SWOT cross-over points during either the one-day Fast Repeat Orbit or the Science Orbit.

7.2.5.1.4 Pre-launch Site Characterization

The tasks for pre-launch characterization of the Cal/Val sites will include:

- Interfacing with country representatives to determine willingness to participate.
- Selection of appropriate gages, given the criteria above.
- High-accuracy GNSS measurements at the location of the stage recording gage and temporally tied to the stage record.

7.2.5.1.5 Post-launch Cal/Val Activities

Post-launch Cal/Val activities are primarily related to data processing and synthesis, with perhaps some minimal field work to check any discrepancies in the gaging data.

7.2.5.2 Tier 2 Lake Sites (U.S./France Joint Project)

7.2.5.2.1 Site Description

Each Tier 2 Lake Cal/Val site will include a stage recorder, which is most likely located near the lake shore. Each of these stage recorders will be surveyed to high-level GNSS accuracy, with survey-grade being possible in most cases, by either SWOT Team Members or by the host country representatives. The corresponding GNSS measurement will be related to the stage recorder measurement spatially and temporally. For the Lake Cal/Val sites, some associated fraction of lake area will need to be identified as consistent with the stage recorder because the lake point measurement will not be universally applicable to the entire lake.

7.2.5.2.2 Site Goals

The goals of the Tier 2 Lake Cal/Val sites are to validate the absolute height, random height error, layover flagging, range drift, and roll/phase drift. Validation of some of these errors will be particularly important to evaluate when the measurements are far from the ocean, where calibration using the altimeter is not possible. In addition, for some of the Tier 2 sites located near meteorologic stations, it may be possible to evaluate wet-tropo delay errors and potentially the rain- and ice-flag data products.

7.2.5.2.3 Site Instrumentation

At each of the Tier 2 Cal/Val sites, it will be determined that the stage recorder is of sufficient accuracy for measuring water-surface elevations, such that the recorder meets or exceeds USGS gaging standards, and that the data are recorded at hourly or more frequent time intervals. In addition, sites with web- or real-time data availability will be given preference, though in some countries, these types of gages are not used and data is recorded offline to be published later.

7.2.5.2.4 Pre-launch Site Characterization

The tasks for pre-launch characterization of the Cal/Val sites will include:

- Interfacing with country representatives to determine willingness to participate.

- Selection of appropriate gages, given the criteria above.
- High-accuracy GNSS measurements at the location of the stage recording gage and temporally tied to the stage record.

7.2.5.2.5 Post-launch Cal/Val Activities

Post-launch Cal/Val activities are primarily related to data processing and synthesis, with perhaps some minimal field work to check any discrepancies in the gaging data.

7.2.6 Corner Reflector/Transponder Calibration Sites

7.2.6.1 Oklahoma/Kansas Sites (US Project Site)

7.2.6.1.1 Site Description

This site is comprised of an array of corner reflectors located at the fast-sampling crossover diamond over Oklahoma, Texas, and Kansas. The corner reflectors will nominally be arranged in an east-west line to span the swaths of the ascending and descending orbits. Specific locations for each corner reflector will be chosen based on the following criteria:

- Access to the site and logistical ease of installation, maintenance, and removal
- Stability of the reflector, including avoiding disturbances in target position or attitude from humans, livestock, wildlife, vegetation growth, weather, etc.
- Flatness of the surrounding terrain in order to simplify the interpretation of the data. The surroundings must at least be flat enough to provide a clear view of the sky for good GPS tracking when surveying the positions of the reflectors.
- Avoidance of features that may be bright enough to contaminate the corner reflector echoes
- Avoidance of overhead vegetation that may attenuate the RF signal (vegetation would also make access and maintenance more difficult)
- Even spacing of reflectors in the cross-track direction
- Minimal but slight staggering of the reflectors in the along-track direction in order to isolate the target impulse responses while ensuring that the targets are imaged over a short enough period of time that variations in instrument state are minimized.
- Ability to image reflectors in both ascending and descending passes in order to maximize the benefit of each reflector

Seven corner reflectors will be arranged across each of the KaRIn swaths (14 total), giving a cross-track spacing of approximately 7 km, commensurate with the sampling required for the science objective of resolving 15 km wavelengths.

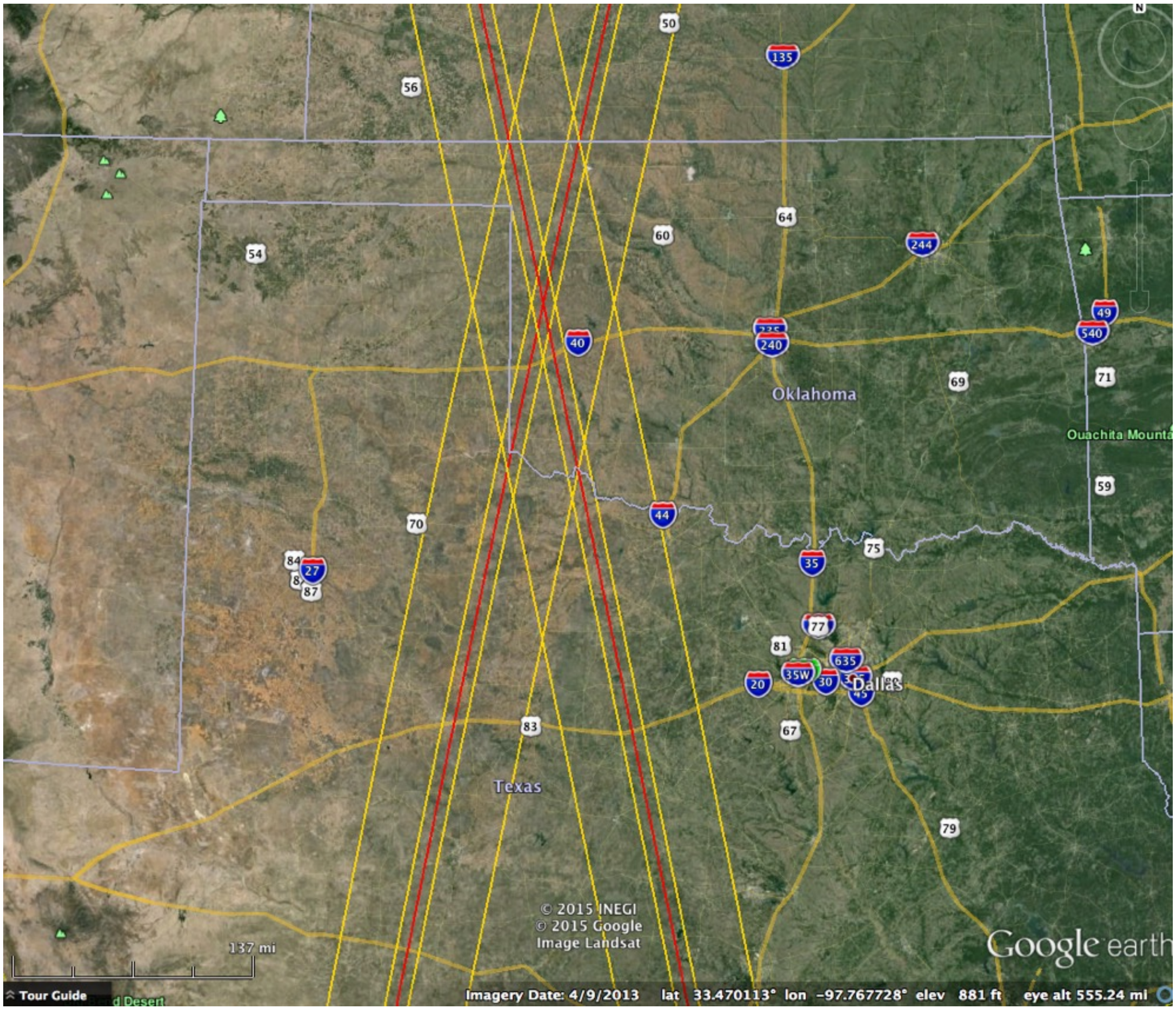


Figure 80. US corner reflector site at the Oklahoma crossover of the 1-day orbit.

7.2.6.1.2 Site Goals

Arrays of corner reflectors are commonly used for the calibration and low-level validation of SAR systems. They will be used to provide coarse, initial estimates for the absolute and differential range delays, to validate point target responses and geolocation accuracy, and secondary phase screen validation.

7.2.6.1.3 Site Instrumentation

The locations of the corner reflectors will be surveyed with GPS instruments to centimetric accuracy prior to the instrument checkout phase of the mission. If there is evidence that the corner reflectors have been disturbed (inconsistencies in heights, horizontal position, or reflectivity in SWOT data, or knowledge of extreme weather, etc.), maintenance of the affected reflectors will be done as necessary and the reflectors resurveyed. The reflectors will be surveyed once again before they are taken down.

7.2.6.1.4 Pre-launch Site Characterization

Pre-launch activity consists of the following:

- Identifying the specific locations of all corner reflectors, coordinating with local landowners or organizations to secure access permissions, etc.
- Designing and building the corner reflectors, or identifying and securing existing corner reflectors. This includes the electrical design (size, triangular trihedral vs. other shape, etc.) as well as mechanical mounting and surveying provisions.
- Development of the detailed plan for who will deploy and survey the reflectors, when deployment will occur, how as-needed maintenance will be pursued, and how/when the reflectors will be taken down.
- Deployment of the corner reflectors, including surveying. This may also occur after launch but prior to KaRIn checkout.
- Imaging the corner reflectors with AirSWOT would provide a useful validation of their setup for risk reduction purposes but is not strictly required.

7.2.6.1.5 Post-launch Cal/Val Activities

Post-launch activity consists of the following:

- Deployment of the corner reflectors if this was not done before launch (deployment must occur prior to KaRIn checkout). Waiting until as late as possible may minimize the likelihood of the reflectors being disturbed.
- Maintenance of the corner reflectors in the event of extreme weather or inconsistencies in the KaRIn data.
- Removal of the corner reflectors, including a survey of the reflector positions.

7.2.6.2 Australia Sites (US Project Site)

7.2.6.2.1 Site Description

The Australian corner reflector site is analogous to the US corner reflector site described above. A second site is needed in order to detect and diagnose effects that have a latitude dependence (the SRTM processor had a software bug that was diagnosed through the use of a secondary corner reflector site in Australia) and to provide corroborating a backup site to the primary US site. This site will be located at the fast-sampling crossover diamond near the Bass Strait in Australia, providing synergistic validation with any Bass Strait data or experiments. The number of reflectors for this site may be reduced as a descope option, though doing so reduces the robustness of the Cal/Val program to unexpected problems encountered after launch.

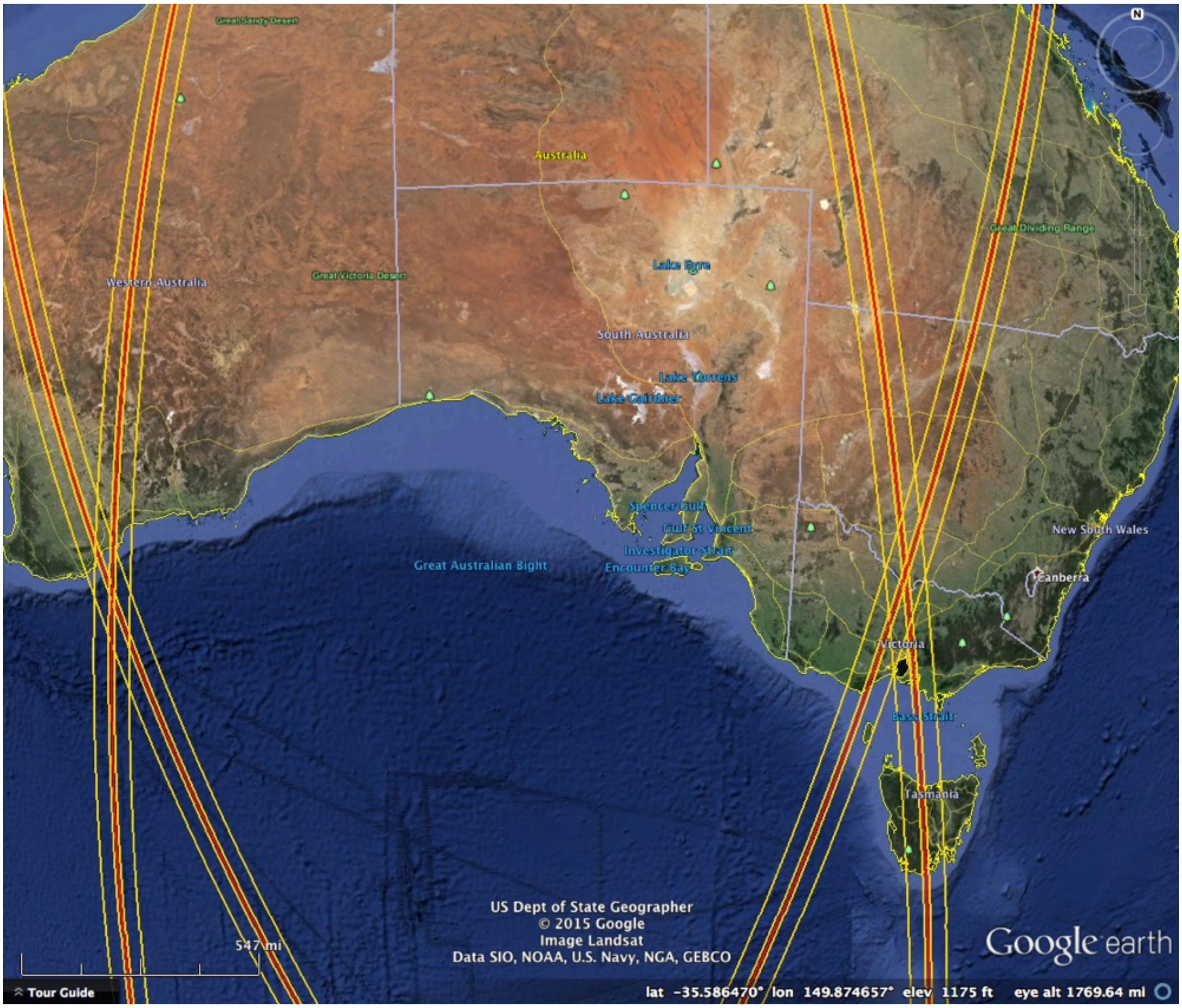


Figure 81. Australian corner reflector site at the 1-day crossover in southeastern Australia.

7.2.6.2.2 Site Goals

Same as for the US corner reflector site, but at a different latitude.

7.2.6.2.3 Site Instrumentation

Same as for the US corner reflector site. Simplification may be a descope option.

7.2.6.2.4 Pre-launch Site Characterization

Same as for the US corner reflector site. Simplification may be a descope option.

7.2.6.2.5 Post-launch Cal/Val Activities

Same as for the US corner reflector site. Simplification may be a descope option.

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Appendix A. SPECIFIC RESOURCES REQUIRED AND TIMING OF ACTIVITIES FOR THE INLAND HYDROLOGY CAL/VAL PROGRAM

The following appendix describes the timing of activities and the specific resources required for the components of the Inland Hydrology Cal/Val program of SWOT.

B.1 Absolute inland surface water height validation - timing of activities and resources required:

Pre-launch:

- 2016. Staff time to analyze past AirSWOT data from Willamette, Sacramento, Tanana and Yukon Flats to understand cross-channel height variability, curvature of river slopes. Staff time, travel and equipment to conduct pressure transducer tests of wind setup on lakes 10 km across and smaller.
- 2016 or 2017. Staff time, travel and equipment to conduct GPS campaign on Lower Mississippi to understand cross-channel heights & curvature effects.
- Spring 2019. Staff time, AirSWOT overflights, travel and equipment to perform dry run for river Cal/Val on the Willamette, including installation of pressure transducers. Lidar flights over the Willamette also required. Agree by this time on acceptable equipment, techniques, measurement methods, etc.
- 2018-launch: Staff time, travel and equipment to obtain all permissions for installation of Cal/Val equipment & conduct measurements at all Cal/Val sites. Work with USGS to survey in all gauges to be used in SWOT height & slope validation.

Post-launch:

- Staff time, travel and equipment to deploy field teams to the Tier 1 sites to check data capture and collect GPS drifter data of water surface elevation.

Tier 2 Cal/Val sites - timing and resources required

Pre-launch:

- Staff time to set up international agreements and agree to data transfer formats. Staff time to create the database. Payments to buy data if necessary.

Post-launch:

- Staff time to manage data sharing agreements and collate database.

B.2 Inundated surface area validation - timing of activities and resources required:

Pre-launch:

- 2016 to 2017. Staff time to analyze past AirSWOT data from Willamette, Sacramento, and Tanana to understand ability of AirSWOT to meet requirements for validation. Staff time to test methods for extracting inundation extents from lidar DEMs and water surface elevations.
- Spring 2019. Staff time, AirSWOT overflights, travel and equipment to perform dry run for river cal/val on the Willamette. Lidar flights over the Willamette also required. Agree by this time on acceptable equipment, techniques, measurement methods, etc.
- 2018-launch: Staff time and budget to collect sample aerial images over a portion of all field sites using the providers likely to be used during post-launch campaigns.
- 2019-launch: Staff time to assemble and analyze all useable lidar DEMS over tier 1 and tier 2 sites that can be used to estimate inundation extent.

Post-launch:

- AirSWOT flights or flight time for other platform to collect necessary imagery. Funding for field teams to deploy on-the-ground measurements. Staff time to analyze lidar, field, and airborne data.

B.3 Small lake inundated surface area - timing of activities and resources required:
Pre-launch:

- 2016 to 2017. Staff time to analyze past AirSWOT data from Yukon Flats to understand ability of AirSWOT to meet requirements for validation. Staff time to test methods for extracting inundation extents from lidar DEMs and water surface elevations.
- 2018-launch: Staff time and budget to collect sample aerial images over a portion of all field sites using the providers likely to be used during post-launch campaigns.
- 2019-launch: Staff time to assemble and analyze all useable lidar DEMS over tier 1 and tier 2 sites that can be used to estimate inundation extent.

Post-launch:

- AirSWOT flights or flight time for other platforms to collect necessary imagery. Funding for field teams to deploy on-the-ground measurements. Staff time to analyze lidar, field, and airborne data.

B.4 Lake lake inundated surface area validation - timing of activites and resources required:
Pre-launch

- 2016-2019: Staff time to develop height/inundation extent rating curves for many lakes, globally (to be led by French).

Post-launch:

- Staff time to download and process satellite imagery coincident with SWOT overflights (to within +/-3 days for most lakes) and to compare SWOT inundation extents against values derived from rating curves.

B.5 Wetland inundated surface area validation - timing of activities and resources required:
Pre-launch:

- 2016-2017: Staff time to analyze data collected in 2015 over Mississippi Delta and Yukon Flats to determine SWOT ability to measure inundation extent under vegetation of various densities and elevations.
- 2017-2018: AirSWOT campaign to either Mississippi Delta or Everglades to characterize SWOT ability to measure inundation extent under vegetation, contingent on outcome of analysis of 2015 campaigns. This is likely to be necessary in part because AirSWOT swath covering SWOT incidence angles in detail was not collected over Mississippi in 2016.

Post-launch:

- UAVSAR and lidar flights over field sites. Staff time to process and analyze resulting data and to download and process relevant satellite imagery over wetland sites.

B.6 Slope Validation - timing of activities and resources required:
Pre-launch:

- 2016 or 2017. Staff time, travel and equipment to conduct GPS campaign on Mississippi to understand cross-channel heights & curvature effects.

- 2016-2017: Staff time to analyze and compare slopes from all methods proposed above on the Sacramento, Willamette, Tanana, and Mississippi Rivers. Goal is to verify that accuracy requirements can be met.
- Spring 2019. Staff time, AirSWOT overflights, travel and equipment to perform dry run for river cal/val on the Willamette, including installation of pressure transducer array. Lidar flights over the Willamette also required. Agree by this time on acceptable equipment, techniques, measurement methods, etc.
- 2018-launch: Staff time, travel and equipment to obtain all permissions for installation of cal/val equipment & conduct measurements at all cal/val sites. Work with USGS to survey in all gauges to be used in SWOT slope validation.
- 2019-launch: Install pressure transducer arrays in all Tier 1 river sites.

Post-launch:

- Staff time, travel and equipment to deploy field teams to the Tier 1 sites to check data capture and collect GPS drifter data of water surface slope. AirSWOT flights over at least three rivers (Willamette, Connecticut, Mississippi) to validate slopes over reach lengths >50 km.