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Monitoring intertidal topography using the future SWOT (Surface Water and Ocean Topography) mission

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Abstract

Intertidal flats are very dynamic environments pressured by anthropogenic activities and climate change. There is an increasing need for updated intertidal topography maps for scientific and coastal management purposes. The future wide-swath altimetry mission SWOT (Surface Water and Ocean Topography) will provide valuable data for intertidal topography monitoring. SWOT will use interferometry to measure heights over water surfaces only, which will prevent the use of this method over intertidal areas. Since SWOT is expected to provide highly accurate 2D sea level measurements in coastal areas, it will be very beneficial for the waterline method. The waterline method is one of the most commonly used spaceborne methods for mapping intertidal topography. This method uses a combination between a series of satellite images acquired at different tidal stages (radar or optical) and sea level information (tide gauge records, models output, or satellite measurements). The aim of this study is to investigate the performance of SWOT in generating intertidal Digital Elevation Models (DEMs) using the waterline method (with a brief investigation regarding the interferometric capabilities of SWOT over intertidal areas). To this end, tests were made by generating intertidal DEMs from SWOT-type observables for two intertidal bays situated on the French coast: the Arcachon Bay and the Bay of Veys. SWOT-type observables were simulated using the SWOT large scale simulator developed by the French space agency (CNES - Centre National d'Etudes Spatiales). By comparing SWOT-derived DEMs to the validation DEMs (generated by the waterline method using Sentinel-1 and -2 images), SWOT showed a great potential for monitoring intertidal topographies. Mean Absolute Errors (MAE) and Root Mean Squared Errors (RMSE) reached respectively 5.2 cm and 8.4 cm for the Arcachon Bay and 10.2 cm and 17.3 cm for the Bay of Veys. However, the accuracy of SWOT is dependent on SWOT's orbit. An unfavorable sampling due to tidal aliasing decreases the accuracy of the DEMs. Thus, the period during which the series of satellite images are acquired (the acquisition period) shall be chosen carefully in order to generate accurate SWOT DEMs. SWOT will be able to generate relatively accurate DEMs with period of acquisitions of 3 months. With acquisition periods that provide adequate sampling of the tidal range. SWOT will be able to detect topographic changes between consecutive DEMs. The present work was supported by the CNES in the framework of the future mission SWOT.

Keywords: SWOT; Intertidal flat; Waterline; InSAR; Topography; DEM.

1. Introduction

Coastal areas are very complex systems with diverse morphology and landforms. The hydrodynamics and morphodynamics in coastal systems are governed by the interactions between three elements: coastal processes (i.e. waves, tides, currents, wind, river outflow, weathering in rocky coasts, and other biological, biophysical, and biochemical processes), sediment transport (erosion and deposition), and morphology (morphodynamic feedback due

to the strong links between form and process (Cowell et al., 1995)) (Masselink and Gehrels, 2015). Over time, the morphological changes alter the hydrodynamic and the sediment transport patterns of the system. Therefore, the continuous monitoring of the topography is fundamental for hydrodynamic and morphodynamic modelling in coastal systems (Catalão and Nico, 2017).

Intertidal zones alternately exposed and covered by water due to the tidal regime are amongst the most logistically challenging coastal landforms for ground-based or airborne-based monitoring of their topography. Spaceborne-based monitoring is therefore, the only viable and cost-effective approach able to provide updated intertidal topography maps (Benveniste et al., 2019; Salameh et al., 2019). Various methods exist nowadays for generating intertidal DEMs from remote sensing data (see Salameh et al. (2019) for a recent review), including Interferometric Synthetic Aperture Radar (InSAR) (Choi and Kim, 2018; Lee and Ryu, 2017), stereoscopy (not a valid option for SWOT), (Tateishi and Akutsu, 1992) (Liu et al., 2013) and the waterline method (Mason et al., 1995). Since SWOT is a radar interferometer, the InSAR method should be prioritized for usage in order to extract intertidal topography. However, the InSAR processing of SWOT observations will be performed over water surfaces only, and other surface types, such as tidal flats, will be discarded. InSAR processing could be performed as well outside the water mask by using SWOT single-look-complex (SLC) images, but these SLC images will be accessible to a small number of scientists, in very limited areas. Their distribution is limited given their large data volume. This leaves us with the waterline method which is, to this day, the most commonly used method to generate intertidal DEMs.

The waterline method consists in extracting the waterlines (shorelines) from a series of remote sensing images acquired at different tidal stages. Then, heights are assigned to the waterlines using sea level information measured by tide gauges or extracted from hydrodynamic models. Finally, the leveled waterlines are assembled and interpolated to produce a gridded-DEM. Intertidal DEMs were generated using the waterline method in various regions especially over the English coasts (Lohani, 1999; Mason et al., 1999, 1995), the Wadden Sea in northern Europe (Heygster et al., 2010; Li et al., 2014; Niedermeier et al., 2005), the Sea Radial Sand Ridges in the Southern Yellow Sea (Kang et al., 2017; Liu et al., 2013; Wang et al., 2019), and more recently in the Bay of Bengal delta (Khan et al., 2019) and the Arcachon and Veys Bays located on the Atlantic Façade of the French coast (Salameh et al., 2020).

Images acquired from radar (Synthetic Aperture Radar - SAR) and optical systems can be used as inputs for the waterline method. The main difference between these two types of data is the edge detection technique that is applied to extract waterlines. Waterlines extracted from optical images can be more easily extracted (Heygster et al., 2010). However, SAR data are more suited for this method due to the ability of SAR sensors to acquire images at all weather conditions, and during day and night (Mason et al., 1999) which enables a finer sampling of the tidal range. Previous studies used remote sensing images acquired by a wide variety of SAR (e.g., ERS-1/2, RadarSat-1/2, EnviSat, JERS-1, COSMO-SkyMed, TerraSAR-X, Sentinel-1 etc.) and optical sensors (e.g., Landsat, IRS, SPOT, IKONOS, Quickbird, MOS-1, Sentinel-2 etc.) to generate intertidal DEMs using the waterline method.

As the waterline method relies on detecting the water/flats interface and on sea level information, it is worthwhile to investigate the performance of the forthcoming SWOT mission to generate intertidal DEMs using this method. SWOT will be the first wide-swath interferometric altimeter that, unlike conventional altimeters, will measure the surface water elevation in 2 dimensions (in wide swaths), providing surface water elevation together with water extents (water masks) (Durand et al., 2010). Such measurements allow the extraction of waterlines directly from water masks. Since SWOT will provide sea surface height information at high accuracy (Morrow et al., 2019), height will be associated to waterlines without the need of ground-based measurements or modelling of water elevation which will make this method completely independent from in-situ measurements. The major issue encountered by the waterline method is the need for a sufficient number of remote sensing

images that covers the tidal range in a short period of time. This is crucial in order to avoid the morphological changes that could occur during the period of acquisition. With an observation frequency of 2–3 times at the equator and up to 6-7 times at high latitudes, within a 21-day period, SWOT has a great potential to provide reliable intertidal DEMs.

Dealing with Sea Surface Height related or dependent measurements in coastal areas using satellite data can lead to sampling- and aliasing- related difficulties. Turki et al. (2015) have investigated the capabilities of SWOT measurements to infer the temporal variability of the sea level along the English Channel coasts in the northwest of France using statistical approaches. The synthetic SWOT samples simulated from the temporal measurements of water levels and SWOT's orbit showed some issues related to the aliasing frequency which increase with the number of overpasses per repeat orbit. As the waterline method requires an adequate sampling of the tidal range, tidal aliasing is expected to be a possible issue for this method as well. This is not the case for the InSAR method because a single pass over the area during low tide is sufficient to extract the intertidal topography.

Various SWOT data simulators were developed to help scientists and SWOT data users get familiar with SWOT products and to help them explore and test new methodologies. Such simulators are the SWOT LR (Low Rate mode) ocean simulator, the SWOT HR (High Rate mode) hydrology simulator developed by the Jet Propulsion Laboratory (JPL), and the SWOT large scale simulator developed by the French space agency (CNES - Centre National d'Etudes Spatiales). The SWOT HR simulator was used by Chevalier et al. (2019) to assess the accuracy of future SWOT data in the Seine Estuary characterized by a strong hydrodynamic variability. The SWOT HR simulator was used in this study to generate SWOT data in order to investigate briefly the potential of the InSAR method, while SWOT waterline-derived intertidal DEMs were generated using SWOT-type observables simulated by the SWOT large scale simulator (CNES, 2020).

In this context, we investigated the ability of SWOT to measure the topography in intertidal areas for two intertidal bays located on the French Coast: the Arcachon lagoon and the Bay of Veys. The potential of the InSAR method (only for the Arcachon Bay) and the waterline method were assessed. For the InSAR method, no DEMs were generated because the SWOT HR simulator provide reliable interferometric processing for water surfaces only. The potential was discussed based on coherence maps generated from SWOT SLC simulated images. For the waterline method however, SWOT-derived intertidal DEMs were generated. The potential of this method was assessed by examining the impact of the SWOT sampling scheme (orbit) and the acquisition period on the accuracy of the generated DEMs. In a final step, an assessment of the ability of SWOT to detect intertidal topographic changes using the waterline-derived DEMs was also performed. The present work was supported by the CNES in the framework of the future mission SWOT.

2. SWOT mission

Recommended by the National Research Council decadal survey "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond" (National Research Council, 2007), SWOT mission, projected for launch in 2021, will last for at least 3 years. SWOT is a collaboration between the National Aeronautics and Space Administration (NASA) and the French space agency (CNES) with contributions from the Canadian Space Agency (CSA) and the United Kingdom Space Agency (UKSA). Its main objectives are to provide surface water topography measurements with a higher coverage and a higher spatiotemporal resolution than conventional altimeters in order to resolve the oceanic mesoscale and submesoscale circulation, and to extend the altimetric coverage to continental surface waters (Fu et al., 2012). SWOT will orbit at an altitude of 890.5 km, on a non-Sun synchronous orbit, with an inclination of 77.6°, and a 20.86-day repeat cycle (Biancamaria et al., 2016). The mission's main instrument will be a Ka-band Radar Interferometer (KaRIn) operating at a frequency of 35.75 GHz (wavelength of 8.6 mm) (Fjortoft et al., 2014). KaRIn is a bistatic SAR system with two antennas at opposite ends separated by a 10-m boom with

near nadir look angles between 0.6° and 3.9° (Fjortoft et al., 2014). The two antennas transmit the radar signal and receive the backscattered signal providing observations in a 120 km wide swath (50 km from each side with 20 km gap) (Fjortoft et al., 2014). SWOT's payload includes as well a conventional altimeter that will be used for validation and calibration of the interferometric measurements and will also allow to fill the gap between the swaths (Srinivasan et al., 2015). In contrast to conventional altimetry missions intended to ocean surfaces only, SWOT mission will provide high precision measurements of water surface elevation over oceans, coastal, and inland water surfaces. Rivers larger than 100 m width and lakes (wetlands and reservoirs) of areas greater than 250 km² will be resolved with a vertical precision of 10 cm. Over terrestrial and coastal waters, SWOT will provide water elevation, slope, and water mask measurements (Biancamaria et al., 2016) with a horizontal resolution of 2.5 m in the azimuth direction (along-track) and a varying resolution in the range direction with pixel sizes that ranges between ~60 m in near range and ~10 m in far range (Fjortoft et al., 2014).

3. Study sites

The current study was achieved by generating SWOT-type observables for two intertidal bays located on the French Coast (Figure 1): the Arcachon Bay and the Bay of Veys. The former is a shallow mesotidal coastal lagoon located in the southeastern part of the Bay of Biscay and the latter is a shallow estuarine embayment located on the southern shore of the English Channel.



Figure 1. (a) An overview map with the location of the study sites: (b) the Arcachon Bay and (c) the Bay of Veys. (a) includes the coverage provided by SWOT's orbit; (b) and (c) include the intertidal flats and the rivers and canals flowing into the two intertidal bays.

3.1. Arcachon Bay

The tides in the Arcachon Bay are semi-diurnal with a weak diurnal inequality and a tidal range that can reach up to 4.6 m during spring tides. The bay receives freshwater from rivers, canals, and groundwater. The Eyre River and the Porges Canal are the major freshwater tributaries contributing about 73% and 24% of the total annual freshwater inputs, respectively (Plus et al., 2009). The surface of the intertidal area uncovered at low tides is about 115 km². These intertidal flats are composed of a mix of muddy and sandy material and a large area (70 Km²) of the flats are vegetated by Zostera noltii seagrass (Blanchet et al., 2005; Proença et al., 2019). They are drained by tidal creeks and channels with a maximum depth around 20 m (Deborde et al., 2008).

3.2. Bay of Veys

The Bay of Veys is located in a semidiurnal macrotidal environment with a tidal range that reaches 8 m at spring tides (Grangeré et al., 2009). Several coastal streams and four main rivers (the Aure, the Douve, the Taute, and the Vire) contribute to the freshwater input into the bay (Grangeré et al., 2009; Lafforgue et al., 2018). The Vire is the largest river flowing directly into the bay and provides 40% of the freshwater input (Grangeré et al., 2009). At low tides, the surface of the uncovered intertidal flats is about 37 km² (Grangeré et al., 2009; Timsit et al., 2004) with a lower part devoid of vegetation and covered by muddy and sandy sediments and an upper part (near the land) colonized by halophytic species dominated by Spartina anglica (Deroin, 2012; Timsit et al., 2004).

4. Datasets and Methods

The current investigation aims to evaluate the performance of SWOT to generate intertidal DEMs by using the InSAR and the waterline method. In the following subsections, brief explanations of the methods are given along with the datasets and workflows used to generate virtual SWOT-type observables. It should be noted that all types of data used and generated in this study are referenced or converted to the French Reference System NGF/IGN69.

4.1. The InSAR method

The InSAR method extract topography information from the phase difference of two (or more) complex SAR images acquired from different perspectives (master and slave images; Z_1 and Z_2 below). In order to investigate the interferometric abilities of SWOT to generate intertidal DEMs, SWOT-type data were simulated using the SWOT HR simulator. The latter generates SWOT data according to SWOT's technical characteristics and expected performance. The simulator takes as input the SWOT orbit, radar parameters, a DEM, and the landtype (with the corresponding backscattering coefficient models of each type) of the observed area. The DEM and the landtype map were provided as if SWOT was observing the intertidal area of the Arcachon Bay at low tide.

The DEM used as input is a Lidar-derived DEM subset, extracted from the RGE ALTI[®] product (acquisitions were acquired on 25 June 2013 at low tide). The dataset is provided on a regular 1×1 m grid and interpolated on a 10×10 m grid (Figure 2.a). The landtypes of the intertidal area (Figure 2.b) used as input were inferred from a Sentinel-2B Multispectral image acquired in 26/09/2018 at low tide. The classification of the image pixels was executed using a k-means clustering algorithm based on the following image bands: B1, B2, B3, B8, B8a, B11, and B12.



Figure 2. (a) Lidar-derived DEM of the intertidal area of the Arcachon Bay extracted from the RGE ALTI® product provided by the national institute for geography and forest information (IGN)); (b) Landtype classes extracted from a Sentinel-2B Multispectral image using a k-means clustering algorithm.

As a first step, the simulator is used to determine the ascending and descending orbits covering the area of interest. The simulator showed that the Arcachon Bay is covered by three SWOT orbits (passes) during a cycle of 21 days. A simulation for each pass was made in order to examine the impact of the localization of the site in the swath. For each pass, the simulator then generates the SLC images acquired by SWOT from which interferograms can be created and used to reconstruct heights. However, the simulator generates heights only over water surfaces (which will be the case for the real SWOT observations) and surfaces outside the water mask will be excluded from the InSAR processing. In consequence, it was not possible to generate intertidal DEM using InSAR method, but the simulated data (SLC images) allow the estimation of coherence maps, a fundamental parameter to assess the interferometric potential of SWOT in intertidal areas (in case SLC images and it is locally computed as follows:

$$\gamma = \frac{E[Z_1 Z_2^*]}{\sqrt{E[|Z_1|^2]E[|Z_2|^2]}} \tag{1}$$

where E[x] is the expected value of random variable x.

4.2. The waterline method

SWOT-type observables needed for applying the waterline method were simulated by the SWOT large scale simulator. In this section, a description of the waterline method and datasets used will be given, followed by a presentation of the SWOT large scale simulator. Then, a stepby-step explanation of the methodology used to generate SWOT-derived DEMs using the waterline method will be provided.

The method consists in detecting the waterline (shoreline) edge of remotely sensed images using image processing techniques. Heights are then attributed to waterlines using water level information obtained either from a hydrodynamic tide/surge model outputs over the observed area at the time of acquisition of the image or from tide gauge measurements (Mason et al., 1995). From a series of images providing adequate sampling of the tidal range, a set of waterlines is assembled and then interpolated to form a gridded-DEM. A detailed description of this method can be found in Mason et al. (1995) and Heygster et al. (2010). As mentioned earlier, the waterlines are extracted from remote sensing images using edge detection techniques which is also a valid option for SWOT (by using SWOT SAR images). However, SWOT will provide water mask measurements from which waterlines can be extracted directly without prior processing. These water masks SWOT-type observables can be simulated by the SWOT large scale simulator.

4.2.1. SWOT large scale simulator

The SWOT large scale simulator (CNES, 2020) is developed by the CNES to simulate, jointly with RiverObs (JPL, 2020) developed by the JPL, SWOT-type virtual (HR) data. The objectives behind this software and other SWOT simulators are to provide open source tools for endusers to simulate and get familiar with SWOT products and to test or propose methodologies that could use SWOT data. The simulator provides data with realistic error: random errors (phase noise related to thermal noise and decorrelation; simulated according to the SWOT error budget) and systematic errors (residual errors from wet troposphere correction). It should be noted that, one important error that was not considered in this study, is the residual roll error. This is a systematic error, varying in time but with a large-scale spatial component, and can be considered as a bias in each SWOT tile. This error is corrected using the roll calibration technique applied to SWOT cross-over points over the ocean (Dibarboure and Ubelmann, 2014). This error is estimated during the ocean processing (LR mode) and is propagated over land surfaces during the hydrological processing (HR mode). However, the accuracy of the correction on the continents is highly dependent on the geographical position: some regions of the globe, far from the ocean crossing points, may have a residual roll error of about 10 cm. This error can therefore have a strong impact in multi-temporal studies. Here, as the study areas are located along the coasts, this error is expected to be negligible.

4.2.2. Datasets

Two types of data were used to generate the input for the SWOT large scale simulator: intertidal DEMs (for each study site for the years 2016, 2017, and 2018) and sea level information.

4.2.2.1. Intertidal DEMs

The intertidal DEMs used here were generated in a recent study (Salameh et al., 2020) by the waterline method using Sentinel-1 and Sentinel-2 images. The datasets are provided on a regular 10×10 m grid. The DEMs were generated for each year using images acquired between the first of June and the end of September.

4.2.2.2. Sea level information

Sea level information used were recorded by the Arcachon-Eyrac tide gauge (1° 9' 48.78" W, 44° 39' 54.003") for the case of the Arcachon Bay. The Arcachon-Eyrac tide gauge has been operational since November 1967 and is currently managed by the French hydrographic service (Service Hydrographique et océanographique de la Marine (SHOM)) and the Gironde sea and land state office (Direction Départementale des Territoires et de la Mer (DDTM)). Since February 2010, the tide gauge is equipped with an Optiwave 7300C sensor and a MARELTA acquisition unit (REFMAR, 2012). Sea level measurements are provided at 1-minute intervals. The data are made available by REFMAR and can be found online on the SHOM data website: https://data.shom.fr.

For the Veys Bay and due to the lack of tide gauge records, sea level data were extracted from the HYbrid Coordinate Ocean Model (HYCOM) (Baraille and Filatoff, 1995). This ocean circulation model is a joint effort between SHOM and Météo-France as part of the HOMONIM (History, Observation and Modeling of sea level) project, which aims to improve the coastal flood warning system in metropolitan and overseas France (SHOM, 2016). Forced by tides (predicted by the SHOM), winds and atmospheric pressure (obtained from Météo-France meteorological models) (Pasquet et al., 2014), the HYCOM model simulates the sea level (tide and surge) on a curvilinear grid and a resolution that ranges between 2 km and 500 m when approaching the French coast. Different configurations of this model exist depending on the geographic domain of the region. Data used here were simulated by the ATL (Atlantic) configuration covering the French Atlantic façade and the English Channel between 43°N 9°W and 62°N 10°E. Hourly gridded forecasts of sea level are provided by the SHOM. However, sea level data were extracted from a single grid-point located at the mouth of the Bay of Veys and interpolated to a 1-minute interval.

4.2.3. SWOT-DEM generation using the waterline method

Different scenarios were simulated to study the impact of the sampling scheme and the acquisition period. In this sub-section, we will present the methodology used to generate a SWOT-derived DEM from the waterline method, accompanied by the results obtained for the first scenario simulated for the Arcachon Bay (A01 – mission start time: 01/01/2016 00:00:00; simulation start time 01/06/2016 00:00:00; simulation end time: 01/10/2016 00:00:00). The methodology steps are the following:

- Determination of all ascending and descending orbits that have swaths containing the area of interest using the orbit selection module of the SWOT large scale simulator. This module takes as input the theoretical SWOT's orbit, the bounding box of the area, the mission start time, and the simulation start and end times. This first simulation will determine the SWOT's orbits and cycles that have swaths containing the study area between the simulation start and end time. The results obtained in this first step for the A01 test are shown in Table 1. Each run in Table 1 is a pass of SWOT over the study area between the simulation's start and end times.
- Assigning water elevation to SWOT's passes using sea level information extracted at the exact time of the satellite overflight of the area. Sea level heights are also shown in Table 1. The tidal coverage provided by SWOT during the acquisition period is shown in Figure 3.a.
- Generating water masks shapefiles from the DEM and the water elevation of SWOT's passes (DEM pixels lower than the water elevation correspond to the water mask). The approximation made here is that the water elevation in the Bay is constant.
- Simulating the pixel cloud (with realistic errors) which consists in water pixels with geolocated heights using the large-scale simulator of pixel cloud (sisimp) module of the simulator. A simulation was made for each run reported in Table 1. This module takes as input the cropped orbits from the orbit selection module, the water mask, and the water elevation.
- Production of water masks shapefiles with their corresponding water elevation from the simulated pixel clouds (of each run) using the Lake processing module (LOCNES –

Lake Observation Cover aNd Extent from SWOT). The Lake processing module was convenient for usage in this study because the water elevation in the Bays was considered as constant similar to a lake, and both of our study sites are located within the SWOT's HR mask.

- Extracting the waterlines from the simulated water masks. The waterlines are the perimeters of the water masks.
- Assigning water elevation of the water masks simulated by the Lake processing module to the waterlines. Examples of three levelled waterlines are presented in Figure 3.b.
- Assembling (Figure 3.c) and interpolation of the waterlines to generate the SWOTderived DEM (Figure 3.d) using the kriging method (Matheron, 1963). Kriging was performed using the Gstat software (Pebesma, 2004; Pebesma and Wesseling, 1998) on grids of 10-m resolution covering the study area.
- Comparing the SWOT-derived DEMs to the original DEMs by computing their Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) which were respectively 9.5 cm and 14.4 cm for the A01 test. The absolute difference map between the two DEMs for the latter test is shown in Figure 3.e along with a density scatter plot in Figure 3.f.

Table 1. The results obtained by the orbit selection module simulating SWOT's swaths covering the Arcachon Bay for the A01 test (mission start time: 01/01/2016 00:00:00; simulation start time 01/06/2016 00:00:00; simulation end time: 01/10/2016 00:00:00) and the attributed sea level obtained from the Arcachon-Eyrac tide-gauge records.

Run	Cycle	Orbit	Date	Time	Sea level	
c008_t348	8	348	07/06/2016	10:59:10	-1.12	
c008_t419	8	419	10/06/2016	00:18:14	-0.46	
c009_t113	9	113	19/06/2016	22:40:22	-1.18	
c009_t348	9	348	28/06/2016	07:44:07	0.15	
c009_t419	9	419	30/06/2016	21:03:11	0.03	
c010_t113	10	113	10/07/2016	19:25:19	1.47	
c010_t348	10	348	19/07/2016	04:29:05	1.80	
c010_t419	10	419	21/07/2016	17:48:09	2.42	
c011_t113	11	113	31/07/2016	16:10:17	1.42	
c011_t348	11	348	09/08/2016	01:14:02	-0.90	
c011_t419	11	419	11/08/2016	14:33:06	-0.42	
c012_t113	12	113	21/08/2016	12:55:14	-1.61	
c012_t348	12	348	29/08/2016	21:58:59	-0.71	
c012_t419	12	419	01/09/2016	11:18:03	-1.15	
c013_t113	13	113	11/09/2016	09:40:11	0.93	
c013_t348	13	348	19/09/2016	18:43:56	2.66	
c013_t419	13	419	22/09/2016	08:03:00	1.96	



Figure 3. Results and simulations obtained for A01 test (mission start time: 01/01/2016 00:00:00; simulation start time 01/06/2016 00:00:00; simulation end time: 01/10/2016 00:00:00): (a) tidal coverage provided by SWOT during the simulation acquisition period; (b) Examples of three levelled waterlines obtained by the end of the simulation which were observed at high, intermediate, and low tides; (c) Assembled waterlines; (d) Gridded SWOT-derived DEM obtained after interpolating the waterlines using the kriging method; (e) the absolute difference map between the original DEM and the SWOT-derived DEM; (f) Original DEM/SWOT-derived DEM density scatter plot.

5. Results and discussion

The general aim of this study is to investigate the performance of SWOT to generate intertidal DEMs. In the following, coherence maps will be presented to discuss the potential of the InSAR method. Then, an assessment of SWOT's performance to generate intertidal DEMs using the waterline method will be provided.

5.1 The InSAR method

SWOT SLC images for the Arcachon Bay were simulated using the SWOT HR simulator for the three orbits covering the Bay (see Figure 1). Coherence maps (Figure 4) were generated from these images owing to equation 1 using a window of 5 pixels width surrounding the pixel of interest (no need to perform flat Earth removal in this case because the kernel is a small 5×5 window). As mentioned in section 2, the horizontal resolution of SWOT varies within the swath between near range and far range (from 60 to 10 m per pixel), with pixels of lower resolution at near range. This variation could alter the quality of the DEMs. Figure 4 shows the poor quality of the results obtained for pass 01 (orbit #348) where the Arcachon Bay within the swath is the nearest to the nadir (near range) compared to the other two passes. Coherence maps with higher quality (resolution-wise) were obtained for passes 02 (orbit #419) and 03 (orbit #113). When analyzing the coherence maps of these two passes to the landtype map (Figure 2.b), low coherence values are present mainly over the vegetated areas (seagrass and salt marshes; less coherent results because the short wavelength of the Ka band interacts with the vegetation). High coherence values are obtained for bare soils, i.e., sandy and muddy surfaces which indicates that this method could be useful for such environments. It should be noted as well, that a NW-SE cross-track gradient in coherence is observed over these areas. This gradient is negative for pass 02 and positive for pass 03. This variation of coherence over the study site for the same landtype could also be explained by the localization of the site in the swath. The Arcachon Bay is localized at far range for both passes but in the right swath for pass 02 and in the left swath for pass 03. This means that the coherence is lower at the extreme side of the swath and this is most likely due to the backscattering coefficient that diminish at far range angles. However, these coherences are still higher than 0.7 and thus the InSAR method could be applied if all the other InSAR-required conditions are reached.



Figure 4. Coherence maps generated from SLC images of: (a) orbit #348; (b) orbit #419; and (c) orbit #113.

Coherence

5.2. The waterline method

As stated earlier, the assessment of SWOT's performance to generate intertidal DEMs using the waterline method relies on the analysis of the impact of the SWOT sampling pattern (i.e. SWOT's orbit), and the acquisition period. The sampling of the waterlines depends on the repeat orbit patterns of the satellite which varies along with the mission start time. Therefore, in order to examine the impact of SWOT's sampling on the accuracy of the generated DEMs, a set of simulations were achieved with the same acquisition period (4 months – between June and September) but with different mission start times. The generated DEMs were compared to the original DEMs by computing the MAEs and RMSEs. The DEM with the lowest error was then used to study the impact of the acquisition period. This was done by simulating other DEMs with shorter and longer acquisition periods but with the same mission start time (that corresponds to the DEM with the lowest error). Finally, the ability of SWOT to detect topographic changes was assessed by generating SWOT intertidal DEMs for 2017 and 2018 in order to create Difference of DEMs (DoD) maps (a qualitative comparison between Sentinel-derived and SWOT-derived DoDs is provided).

5.2.1. SWOT sampling

For each site, 11 simulations were performed by incrementing the mission start time of 6 days starting from 01-01-2016 00:00:00 to 29-02-2016 00:00:00. For all tests, the acquisition period is 4 months with simulations starting in 01-06-2016 00:00:00 and ending in 01-10-2016 00:00:00. The simulated SWOT-derived DEMs were compared to the original DEMs. MAEs and RMSEs for all tests are presented in Table 2. As anticipated, the accuracy of the DEMs vary with the mission start time owing to a coarse sampling or/and sometimes unfavorable aliasing. As can be seen in Table 2, for the Arcachon Bay the MAEs vary between 5.2 cm (A02) and 19.5 cm (A04) and for the Veys Bay between 10.2 cm (V09) and 28.4 cm (V06). The better accuracy obtained for the Arcachon Bay is likely to be due to the better coverage that SWOT provides for the Arcachon Bay. Orbit #141 is cutting the edge of the Veys Bay (Figure 1) which makes the latter covered by 2 orbits only (#320 and #042). It should be noted that in Table 2 and Table 3, orbit #141 was not counted among the number of passes.

Figure 5 shows the tidal coverage (or sampling) provided by SWOT for A02 and A04 tests. It is clear that SWOT covers better the tidal range in A02. For A04, the intermediate part of the tidal range highlighted in blue is mostly unsampled. This unfavorable sampling for A04 is also apparent in Figure 6 (a and b) where waterlines of A02 and A04 are shown.

Figure 6 shows another limitation that SWOT could face while using the waterline method. We can see that the bay is well covered on one side and waterlines are missing on the other side which is due to the swath of orbit #348 cutting the bay in half (Figure 1). This also implies that the unfavorable aliasing originates from the other orbits and not from orbit #348 because this orbit is covering well the other part of the bay. The SWOT-derived DEMs for tests A02 and A04 are shown in Figure 6.c and Figure 6.d and the comparisons with the original DEM in Figure 6.e and Figure 6.f. High errors are located in the right side of the Bay where waterlines were missing. For A02 test, high errors were observed over the "Ile aux Oiseaux (birds island)" where the topography is higher than the highest detected waterline. A higher waterline was detected for the A04 test, which explains the lower errors over the island. Figure 7 shows the comparison between the original DEM and the SWOT-derived DEMs for tests A02 and A04.

Figure 8 shows the tidal coverage provided by SWOT for V09 and V06 tests. For V09, the sampling of the tidal range is almost complete and with a good regularity while for V06 a considerable water level range is not covered. This is also apparent in the Figure 9.a and Figure 9.b showing the extracted waterlines of these two tests. The unfavorable sampling reduced the accuracy of the DEM because a large area of the bay is not covered by waterlines. It is obvious from the DEMs shown in Figure 9.c and Figure 9.d that for V06 test the channels of the bay were not detected due to a lack of waterlines where high differences exist by

comparing to the original DEM (Figure 9.f). Figure 10 shows the comparison between the original DEM and the SWOT-derived DEMs for tests V09 and V06.

Table 2. The comparison results expressed as Mean Absolute Errors (MAEs) and Root Mean Square Errors (RMSEs) between the original DEM and the SWOT-derived DEMs simulated with various mission start time and the same acquisition period. Best/worst cases are highlighted in green/red respectively for the Arcachon and Veys bays.

Study site	Test name	Mission start time	Simulation start time	Simulation end time	Number of passes	Acquisition period (month)	MAE (cm)	RMSE (cm)
	A01	01-01-2016	01-06-2016	01-10-2016	16	4	9.5	14.4
	A02	06-01-2016	01-06-2016	01-10-2016	16	4	5.2	8.4
	A03	12-01-2016	01-06-2016	01-10-2016	17	4	8.5	14.0
	A04	18-01-2016	01-06-2016	01-10-2016	15	4	19.5	30.6
	A05	24-01-2016	01-06-2016	01-10-2016	14	4	7.3	12.5
Arcachon	A06	30-01-2016	01-06-2016	01-10-2016	16	4	9.0	13.9
	A07	05-02-2016	01-06-2016	01-10-2016	13	4	10.2	15.6
	A08	11-02-2016	01-06-2016	01-10-2016	16	4	8.7	12.9
	A09	17-02-2016	01-06-2016	01-10-2016	14	4	12.3	19.6
	A10	23-02-2016	01-06-2016	01-10-2016	15	4	6.9	12.0
	A11	29-02-2016	01-06-2016	01-10-2016	15	4	7.6	12.9
	V01	01-01-2016	01-06-2016	01-10-2016	12	4	11.6	18.4
Veys	V02	06-01-2016	01-06-2016	01-10-2016	12	4	17.6	24.7
	V03	12-01-2016	01-06-2016	01-10-2016	12	4	18.3	30.4
	V04	18-01-2016	01-06-2016	01-10-2016	12	4	15.1	24.0
	V05	24-01-2016	01-06-2016	01-10-2016	11	4	21.1	37.0
	V06	30-01-2016	01-06-2016	01-10-2016	12	4	28.4	50.1
	V07	05-02-2016	01-06-2016	01-10-2016	11	4	13.9	20.8
	V08	11-02-2016	01-06-2016	01-10-2016	12	4	15.0	24.3
	V09	17-02-2016	01-06-2016	01-10-2016	12	4	10.2	17.3
	V10	23-02-2016	01-06-2016	01-10-2016	12	4	22.6	38.0
	V11	29-02-2016	01-06-2016	01-10-2016	12	4	12.8	19.5



Figure 5. Tidal coverage provided by SWOT for tests: (a) A02 and (b) A04.



Figure 6. Results obtained for A02 and A04 tests: (a) and (b) A02 and A04 waterlines; (c) and (d) A02 and A04 SWOT-derived DEMs; (e) and (f) A02 and A04 absolute difference maps between the original sentinel-derived DEMs and the SWOT-derived DEMs.



Figure 7. Sentinel-derived DEM/SWOT-derived DEM density scatter plots for tests: (a) A02 and (b) A04.



Figure 8. Tidal coverage provided by SWOT for tests: (a) V09 and (b) V06.



Figure 9. Results obtained for V09 and V06 tests: (a) and (b) V09 and V06 waterlines; (c) and (d) V09 and V06 SWOT-derived DEMs; (e) and (f) V09 and V06 absolute difference maps between the original sentinel-derived DEMs and the SWOT-derived DEMs.



Figure 10. Sentinel-derived DEM/SWOT-derived DEM density scatter plots for tests: (a) V09 and (b) V06.

5.2.2. Acquisition period

The impact of the acquisition period on the accuracy of the generated DEMs was examined by varying the simulations start times. The objective is to examine the ability of SWOT to provide accurate DEMs for acquisition periods shorter than 4 months and to examine if the obtained accuracy for the 4 months could be improved for acquisition periods longer than 4 months. The acquisition period was reduced from 4 months to 2 and 3 months and increased from 4 months to 5, 6, and 7 months. MAEs and RMSEs for these tests are shown in Table 3. Increasing the acquisition period improved the accuracies from 5.2 cm (4 months) to 4.4 cm (7 months) for Arcachon Bay and from 10.2 cm (4 months) to 6.7 cm (6 and 7 months) for the Bay of Veys. However, this does not mean that increasing the acquisition period using real SWOT data will improve the results because the impact of topographic changes will be too important in such a long acquisition period. This was performed in order to examine if the obtained accuracy for the 4 months acquisition period is limited or could be improved with a higher sampling rate that can be provided by other sensors. Shortening the acquisition period reduced the accuracy of the DEMs. For both study sites, a slight increase was observed for an acquisition period of three months which means that shorter period can be used and more DEMs can be generated within 1-year period. However, a considerable increase was observed for an acquisition period of 2 months where the MAE has nearly tripled.

Table 3. The comparison results expressed as Mean Absolute Errors (MAEs) and Root Mean Square Errors (RMSEs) between the original DEM and the SWOT-derived DEMs simulated with the same mission start time and various acquisition periods.

Study site	Test name	Mission start time	Simulation start time	Simulation end time	Number of passes	Acquisition period (month)	MAE (cm)	RMSE (cm)
Arcachon	A02	06-01-2016	01-06-2016	01-10-2016	16	4	5.2	8.4
	A12	06-01-2016	01-08-2016	01-10-2016	9	2	16.2	25.3
	A13	06-01-2016	01-07-2016	01-10-2016	13	3	6.2	9.5
	A14	06-01-2016	01-05-2016	01-10-2016	21	5	4.9	8.1
	A15	06-01-2016	01-04-2016	01-10-2016	25	6	4.6	7.9
	A16	06-01-2016	01-03-2016	01-10-2016	28	7	4.4	7.9
Veys	V09	17-02-2016	01-06-2016	01-10-2016	12	4	10.2	17.3
	V12	17-02-2016	01-08-2016	01-10-2016	6	2	19.4	30.9
	V13	17-02-2016	01-07-2016	01-10-2016	9	3	12.4	18.9
	V14	17-02-2016	01-05-2016	01-10-2016	14	5	9.4	16.3
	V15	17-02-2016	01-04-2016	01-10-2016	17	6	6.7	11.4
	V16	17-02-2016	01-03-2016	01-10-2016	20	7	6.7	11.5

5.2.3. Monitoring topographic changes

Finally, we investigated the ability of SWOT to monitor topographic changes using DEMs generated with the waterline method over the years. For this purpose, intertidal SWOT-derived DEMs were generated for 2017 and 2018 using 2017 and 2018 Sentinel-derived DEMs. DoD maps for the Arcachon (Figure 11) and Veys (Figure 12) Bays were generated for the 2016/2017 and 2017/2018 using the original Sentinel-derived DEMs and the SWOT-derived DEMs (areas outside the highest and lowest waterlines limits were removed). By comparing the DoD maps of 2016/2017 for the Arcachon Bay, Sentinel and SWOT-derived DEMs showed generally the same patterns of erosion (negative values) and deposition (positive values) with some missed spots and difficulties in areas of lowest and highest tides where no waterlines were detected. In contrast, 2017/2018 DoD map showed more erroneous topographic changes due to a considerable number of missing waterlines in the southeastern part of the bay. Better results were obtained for the Veys Bay where good correspondence was observed for 2016/2017 and 2017/2018.

As was showed earlier, the test A02 (mission start time 06/01/2016) provided the best accurate results comparing to other tests. However, using the same mission start time, the sampling for 2017 and especially for 2018 was not as good as in 2016. This implies, that the continuous change of phase between SWOT's orbit and the tides complicates the monitoring of topographic changes. Rather than choosing the same acquisition period (e.g., June-September) for the monitored years, it is required to change the period in order to generate a DEM from waterlines that cover better the intertidal area (or adding data from other sources).



Figure 11. Arcachon Bay DoD maps generated from: (a) 2017 and 2016 Sentinel-derived DEMs; (b) 2017 and 2016 SWOT-derived DEMs; (c) 2018 and 2017 Sentinel-derived DEMs; and (d) 2018 and 2017 SWOT-derived DEMs.



Figure 12. Veys Bay DoD maps generated from: (a) 2017 and 2016 Sentinel-derived DEMs; (b) 2017 and 2016 SWOT-derived DEMs; (c) 2018 and 2017 Sentinel-derived DEMs; and (d) 2018 and 2017 SWOT-derived DEMs.

6. Conclusions

In this study, we investigated the performance of the future SWOT mission to generate DEMs in intertidal areas using the InSAR and the waterline methods. Two study sites were considered: the Arcachon and Veys Bays located on the French coast.

The InSAR potential was investigated based on coherence maps generated from simulated SWOT SLC images for the Arcachon Bay. High coherence values were obtained for bare intertidal areas. This indicates that precise intertidal DEMs could be generated from SWOT near nadir acquisitions and this new technology has an enormous potential for vast intertidal areas. Several intertidal DEMs can be generated by SWOT from acquisitions made at low tides for a one-year period. However, the unavailability of SLC images (and the interferometric processing over water surfaces only) due to their large volume limits the use of the InSAR method. But it is still crucial to test the interferometric performance of real SWOT data over intertidal areas, such as the Mont-Saint-Michel Bay, to show the real capacities of such technologies for future satellite missions.

For the waterline method, intertidal DEMs were generated for the two Bays using SWOT-type observables simulated by the SWOT large scale simulator. For both study sites, several SWOT-DEMs were generated in order to investigate the impact of SWOT's sampling scheme and the impact of the acquisition period on the DEMs accuracy. The impact of SWOT's sampling scheme was investigated by generating several DEMs with the same acquisition period (4 months; simulation start time 01/06/2016 00:00:00; simulation end time: 01/10/2016 00:00:00) and a varying mission start time, while the impact of the acquisition period was investigated by generating DEMs with the same mission start time and a varying simulation start times (in order to change the acquisition period from 4 months to 2, 3, 5, 6, and 7 months). By comparing to the original DEMs, we have demonstrated that SWOT mission is capable of generating accurate intertidal DEMs on its own. Contrary to current satellite imagers, SWOT will provide water masks and thus the corresponding waterlines with accurate sea surface height from InSAR allowing to account for surface water slope which is not possible when using tide gauge records. However, the DEMs accuracy is strongly dependent on the mission start time (orbit) and the accuracy may decrease due to an unfavorable aliasing. MAEs varied between 5.2 cm and 19.5 cm for the Arcachon Bay and between 11.6 cm and 28.4 cm for the Veys Bay. From shortening and extending the acquisition period we also showed that (i) the acquisition period could be reduced to 3 months and still provide relatively accurate measurements and (ii) improvement in accuracy could be made by extending the acquisition periods and adding more waterlines. However, adding waterlines is preferred to be made by importing data from other sensors while keeping the same short acquisition period, rather than extending it and making the DEM more prone to errors due to topographic changes that may occur.

These findings confirm the benefits of SWOT in monitoring intertidal areas. The waterline method is applicable to intertidal areas located in the SWOT HR mask. Intertidal areas of great interest could be mapped by SWOT such as the Bay of Mont Saint Michel and Bay of Fundy. However, the real added value of SWOT using the waterline method will be for remote, dangerous, and non-instrumented intertidal environments.

In addition to sea surface height, SWOT will be able to generate not one but several intertidal DEMs during a year. Thus, seasonal and interannual topographic changes could be quantified. However due to unfavorable aliasing between the orbit and the tides, the best sampling within a year could occur in different periods for different years. Therefore, care must be taken when choosing the acquisition periods of SWOT to generate intertidal DEMs if no external data from other sources were used to complete the tidal range sampling.

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