The Challenge of Using Future SWOT Data for Oceanic Field Reconstruction

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ABSTRACT

Conventional altimetry measures a one-dimensional profile of sea surface height (SSH) along the satellite track. Two-dimensional SSH can be reconstructed using mapping techniques; however, the spatial resolution is quite coarse even when data from several altimeters are analyzed. A new satellite mission based on radar interferometry is scheduled to be launched in 2020. This mission, called Surface Water and Ocean Topography (SWOT), will measure SSH at high resolution along a wide swath, thus providing two-dimensional images of the ocean surface topography. This new capability will provide a large amount of data even though they are contaminated with instrument noise and geophysical errors. This paper presents a tool that simulates synthetic observations of SSH from the future SWOT mission using SSH from any ocean general circulation model (OGCM). SWOT-like data have been generated from a high-resolution model and analyzed to investigate the sampling and accuracy characteristics of the future SWOT data. This tool will help explore new ideas and methods for optimizing the retrieval of information from future SWOT missions.

1. Introduction

For more than 20 years, nadir altimetric satellites have provided observation of the dynamics at the surface of the ocean. Up to now, only nadir altimeters have been used and have provided measurement along the satellite tracks. The along-track resolution is about 6 km (resolving wavelengths typically larger than 70 km) but as there are wide gaps between two successive tracks, a significant part of the mesoscale dynamics (below 150 km) is missing. Several altimeters are thus needed to provide an assessment of the dynamics at mesoscales (Pasqual et al. 2006; Le Traon and Dibarboure 2002). The resolution of gridded ocean surface topography using two altimeters is limited to wavelengths larger than 150 km (Ducet et al. 2000; Dibarboure et al. 2011), and the use of more altimeters (up to four) improve the accuracy of the mapping. However, it is not possible to observe scales smaller than 120 km even with a constellation of nadir altimeters (Chavanne and Klein 2010; Chelton and Schlax 2003). Therefore, innovative technologies are needed to get access to small mesoscale and submesoscale dynamics.

In this context, the future Surface Water and Ocean Topography (SWOT) mission aims at measuring high-resolution sea surface height (SSH) in two dimensions along a wide swath (Fu and Ubelmann 2014). The oceanography part of the SWOT mission should make it possible to characterize the ocean mesoscale and submesoscale circulation determined from SSH at a spatial effective resolution of 15 km. To do so, a radar interferometer is used in addition to a nadir altimeter. It consists of two synthetic aperture radar (SAR) antennas located on each side of a 10-m-long mast. Each antenna can observe a 60-km-wide swath with an incidence angle of $1^{\circ}$–$4^{\circ}$. The two antennas will receive simultaneously the signal reflected from the ocean surface, and the SSH is obtained from using the difference of phase between the two signals. There is a 20-km gap between the two swaths that will be filled with a nadir altimeter. The intrinsic resolution of SAR is about a few meters, but the measures are averaged to reduce the noise on a 1–2-km grid.

SWOT will provide a large amount of data and should enable the observation of sea surface height at scales that have never been resolved before. However, the technology of the interferometer has its own specific error budget. Therefore, one needs to investigate the capabilities of SWOT and develop methods to process and analyze the large amount of data so that we can fully exploit the data when they are available. To do so, we have created a tool that simulates SWOT-like observations. This tool will be
referred as the “simulator.” The goal of this tool is to simulate synthetic observations of SSH from SWOT that can be applied to an ocean general circulation model (OGCM). Some measurement errors and noise are generated according to technical characteristics published by the SWOT project team. Not designed to directly simulate the payload instrument performance, this SWOT simulator aims to provide statistically realistic outputs using error specification in the spectral domain provided by the SWOT project team.

The preparation of the SWOT mission has raised many scientific challenges, leading to the need to simulate SWOT observations to perform observing system simulation experiments (OSSEs) to address these challenges: 1) the construction of continuously gridded SSH to represent fully the high-resolution signal of the SSH (see section 4); 2) the estimation of high-order derivative variables, such as the vorticity of ocean currents; and 3) the observability of the dynamics that can be retrieved from SWOT.

In the following, the second section provides technical details about the SWOT simulator tool and the third section illustrates the outputs from the tool for analyzing the retrieved signal from the simulated SWOT data. The benefit of a radar interferometer compared to a nadir altimeter is investigated in the fourth section.

2. The SWOT simulator for ocean science

The detailed version of the technical documentation of the SWOT simulator software can be downloaded (http://swot.jpl.nasa.gov/science/resources/); only the main features of the tool are described here. From a global or regional OGCM configuration, the software generates SSH on a 120-km-wide swath at typically 2-km resolution.

The first step is the construction of the SWOT grid. To do so, ground track coordinates of the nadir ground track of the orbit are computed using the baseline orbit with a 20.86-day repeat cycle, an inclination of 77.6°, and an altitude of 891 km (consisting of 292 ascending/descending passes in a repeat cycle). Then, the grid is defined in the across-track directions between 10 and 60 km off nadir. The grid size resolution is 2 km in the along-track and across-track directions.

Once the SWOT grid is generated, input SSH is interpolated on this grid as well as along the nadir track. The SSH is interpolated linearly on the SWOT grid and nadir track for each pass of successive cycles if the input data exceed one cycle. The nadir track has the same resolution as the SWOT grid in the along-track direction. No interpolation is performed in time, meaning that the SSH on the SWOT grid at a given time corresponds to the SSH of the closest time step. Figure 1a shows a snapshot of the SSH at a given time (the “study date”) as an example from the Regional Ocean Modeling System (ROMS) model (Shchepetkin and McWilliams 2005) off the Oregon coast provided by Dr. Yi Chao and his team, and Fig. 1b represents the SSH from the model interpolated on the SWOT grid for 21 days (one cycle) centered on the study date. The software generates random realizations of instrument errors and noise over the interpolated SSH, as well as simulated geophysical errors. These error simulations are adjusted to match potential updates of the error budget estimation from the SWOT project team, and more details on the errors and their spectrum can be found in the project team’s document on the SWOT error budget (Esteban-Fernandez 2014). Figure 2 shows a realization of the SWOT error field generated by the software. It is the sum of random realizations of multiple error components that are described in the following. The simulated total error is added to the SSH interpolated on the SWOT grid to create the SSH as it is observed by SWOT (referred as “SWOT-like SSH”; see Fig. 1c).

Only the major errors expected to impact the SWOT signal are implemented in the simulator: the Ka-Band Radar Interferometer (KaRIN) noise, roll errors, phase errors, baseline dilation errors, and timing errors. Random realizations of the noise and errors are performed following the spectral descriptions of the SWOT error budget document (Esteban-Fernandez 2014). Details about the random generation of the errors can be found in the technical documentation of the simulator software.

The KaRIN instrument noise is random from cell to cell and is defined by a Gaussian zero-centered distribution of standard deviation inversely proportional to the square root of the cell surface. In the simulator, the KaRIN noise varies with the distance to the nadir and the significant wave height (SWH) specified as a constant value between 0 and 7 m. In Fig. 3a, the KaRIN noise is simulated assuming a 2-m SWH. The other instrument errors (roll, phase, baseline dilation, and timing error) are generated using an along-track power spectral density of the error (defined in Esteban-Fernandez 2014). Following the power spectrum of the error, random realizations of the along-track error are performed with a uniform distribution. Each error is then reconstructed on the swath using algorithms from Esteban-Fernandez (2014). The roll error signal (Fig. 3b) is the sum of two components: the roll error knowledge (also called gyro error), which is due to errors in the knowledge in the spacecraft roll angle, and the roll control errors, which is introduced by the KaRIN mechanical system.
The phase error (Fig. 3c) is introduced by each antenna independently and is thus uncorrelated between the two sides (as opposed to all the other instrumental errors). The baseline dilation error (Fig. 3d) is due to the distortion of the mast, which creates a change in the baseline mast. The timing error (Fig. 3e) corresponds to a common group delay error of the system and is constant across track. Both, the timing and the baseline dilation errors are small compared to the other instrumental errors.

As far as geophysical errors are concerned, only the major source of error—the wet troposphere error—is implemented in the software. The software simulates errors in the water vapor path delay retrieval following Ubelmann et al. (2014). To do so, a two-dimensional random signal is generated around the swath following a one-dimensional spectrum with uniform phase and distribution. This spectrum is the global average of estimated path delay spectrum from the Advanced Microwave Scanning Radiometer for Earth Observing...
System (AMSR-E) instrument and from the JPL’s High-Altitude Monolithic Microwave Integrated Circuit (MMIC) Sounding Radiometer (Brown et al. 2011) for the short wavelength.

From the two-dimensional random signal, the software simulates the residual error after correction for the estimated path delay from the radiometer. The radiometer measures the path delay averaged over a two-dimensional Gaussian footprint corresponding to an overall 20-km-diameter beam, close to the characteristics of the Advanced Microwave Radiometer (AMR) radiometer on Jason-2. A configuration with one radiometer (looking at the nadir) or two radiometers (looking at the middle of each swath along the across-track direction) can be used. In Fig. 3f, the path delay has been corrected using only one beam. The remaining error on the path delay after correction is quite significant compared to the other errors (roll error, phase error, and KaRIN noise). The sea state bias (SSB) error is not yet considered here, but it should mainly impact the large scales not of primary interest to SWOT.

The along-track power spectra of the different error components have been computed to check the consistency with the baseline requirements as described in Esteban-Fernandez (2014). These spectra, averaged across track between 10 and 60 km off nadir, are shown in Fig. 4. The total error budget (thick black line) is slightly below the error requirements (thick red line). Note that the along-track power spectrum of KaRIN noise (thick dark pink line) is computed after the noise is

![Fig. 2. Random realization of the error field (m) and swath coordinates (km).](image1)

![Fig. 3. Breakdown of Fig. 2, where each component (m) of the errors has been generated by the simulator: (a) the KaRIN noise, (b) the roll error, (c) the phase error, (d) the baseline dilation error, (e) the timing error, and (f) the path delay remaining error after correction using a one-beam radiometer. Swath coordinates are in kilometers.](image2)
smoothed over the 7.5 km × 7.5 km area, which is the Nyquist for resolving the 15-km wavelength, and is the shortest scale resolved by SWOT (see Fu and Ubelmann 2014).

The simulator tool described in this section is used to simulate SWOT-like level 3 observations thereafter. These synthetic observations are analyzed to determine the scales and the amount of information that can be retrieved from the future SWOT signal.

3. SWOT-like observations of the surface ocean dynamics

The SWOT mission will provide two-dimensional measurements of the SSH at high resolution. Previous studies (e.g., Fu and Ubelmann 2014) have illustrated the richness of the SWOT signal. However, the noise consideration was overly simplified. Therefore, it was difficult to discuss the resolution of the SSH signal from the SWOT mission as the simulated SWOT observations were not realistic. The present study makes it possible to analyze the resolution of the SWOT SSH using a realistic simulation of the observation of the ocean by SWOT.

In Fig. 1c SWOT-like SSH on a 21-day period (centered on the study date; Fig. 1a) are displayed. Each swath is plotted independently and recovers partly the older swaths. Note that the large-scale roll error has already been filtered by the simulator. We can see how noisy the SWOT-like observations are and how difficult it can be to discriminate accurately small-scale signals from errors. Most of the small and mesoscale eddies are still visible in the SWOT-like observations though the edges of the structures are not as sharp as in the truth. Some gaps remain between the swaths (visible as white diamond-shaped features). Small eddies are likely missed or not sampled correctly within these gaps. One can actually see a small eddy in the truth that is partially missed by SWOT [located in the northwest part (47°N, 129°W) of Fig. 1c] as it is right within a diamond-shaped gap.

The two-dimensional measurement of the SSH makes it possible to compute derivatives of the SSH. Therefore, geostrophic surface velocities could be retrieved. The derivatives shown here are computed using a simple first-order difference. A more sophisticated method with wider stencil width (Arbic et al. 2012) or a smooth noise robust differentiator has also been tested. As only few improvements on the derivatives of the SWOT-like observations were visible and many data points around the edges were lost, the velocities are computed using a simple difference between two data points. The geostrophic velocity directly computed from the SWOT-like SSH is shown in Fig. 5b, revealing nothing but noise that is amplified by the derivative calculations. As plotted in Fig. 1d, the SWOT-like SSH is filtered using a spatial optimal interpolation locally on each swath. The geostrophic velocity can now be computed from the filtered SWOT-like SSH and is shown in Fig. 5c. Distinct structures are now visible. Comparing this velocity with the velocity derived from the SSH with no noise (interpolated on the swath) in Fig. 5a, one can see that most structures are visible in the velocity and are correctly represented. Some noise remains, especially on the edge of the swath, where the noise is larger and the data are more difficult to filter. However, if one is interested in higher-order derivatives (e.g., to diagnose vertical velocities, vorticities, or strains), new algorithms need to be developed for more efficient filtering.

The observation of two-dimensional SSH images at a high resolution will give us access to new scales though the high level of noise and errors in the SWOT observations remains an issue, and innovative methods still need to be developed to fully benefit from the large amount of data provided by SWOT. The simulator of SWOT observations presented here is helpful to the development of new ideas.

4. Mapping the SSH

One-dimensional profiles of the SSH from a classic nadir altimeter have been mapped using a temporal and spatial optimal interpolation method similar to the one used in the spatial optimal interpolation method (Bretherton et al. 1976). In this configuration of the Oregon coast, with the dominance of around 150-km-diameter
eddies, we found optimal decorrelation scales of the order of 80 km in space and 8 days in time. For decorrelation functions, we used the same analytical form as in Arhan and De Verdière (1985). The corresponding Lo and To are 80 km and 8 days, respectively. To compare the performance of the future SWOT interferometer with the actual nadir altimeter constellation, the same mapping method as the one used with nadir is set up to optimally interpolate SWOT observation for mapping SSH.

Nadir-like observations are generated using two satellites tracks: Jason-1 and Jason-2. To do so, the SSH is interpolated along these tracks. The instrument and geophysical errors are simulated using a random noise that follows an estimate of the spectrum for nadir altimetry errors. Wet tropospheric errors are computed separately using the same methods as the one described in section 2. Both simulated errors are then added to the interpolated SSH. A cycle (10 days) of Jason-1 and Jason-2 observations centered on the study date is shown in Fig. 6d. Synthetic observations of SSH are mapped using optimal interpolation algorithms in space and time on a 30-day period. Let us call “mapped SWOT” the mapping of the SSH that contains only SWOT-like data during the optimal interpolation (Fig. 6b) and “mapped nadir” the mapping of the SSH using only Jason-1 and Jason-2 nadir observations (Fig. 6c). These mapped products are compared with the true SSH from the model (Fig. 6a). First of all, large mesoscale structures are visible and located correctly. The spatial coherence between the true and the mapped signals (not shown here) shows a good correlation between the mapped observations and the truth at these large scales. At mesoscale and smaller, the benefit of radar interferometry compared to classic nadir altimetry is prominent. We tested various configurations up to four nadir altimeters. In this region of the Oregon coast, one SWOT interferometer still exceeds four nadir altimeters. Many small eddies are represented in the SWOT-mapped product, but they are missing from the nadir-mapped image. Still, the mapped SWOT SSH contains very few small mesoscale features (structures smaller than 50 km) and no submesoscale features (smaller than 15 km), whereas these scales are clearly detected in the originally simulated SWOT data. The lack of resolution in the mapped SWOT and in the mapped nadir products is even more striking in the derivatives of the signal. The geostrophic velocity is derived from the true SSH (Fig. 6e), from the mapped SWOT (Fig. 6f), and from the mapped nadir (Fig. 6g). One can see that the geostrophic velocity from mapped nadir SSH is much too smoothed. The two main large-scale eddies (located on the west part of the domain) are the only features visible. The geostrophic velocity from mapped SWOT SSH shows mesoscale eddies but is still quite smoothed compared to the truth or to the SWOT-like observation in the swath.

Another way of comparing the resolution of the different SSH is the computation of their respective power spectra. For each time and for each longitude, a one-dimensional power spectrum of the mapped SSH is computed along the latitude. The average of all spectra is shown in Fig. 7 (200 sampled spectra were averaged). In this figure, the spectrum computed using model data (the “true SSH”) is plotted in red, in green is the spectrum computed from SWOT-mapped SSH, and in...
blue is the one corresponding to nadir-mapped SSH. The spectrum computed using the simulated SWOT-like observations is plotted in cyan, and the spectrum from the filtered SWOT-like observations is in magenta. Both of these spectra are computed along the track instead of along a fixed latitude. Note that there are no data at scales larger than 250 km, limited by the domain of the model. Other models have been studied and have shown that mapped nadir, mapped SWOT, and the truth have similar power spectra at scales larger than 250 km. Comparing the various spectra, one can conclude that only scales larger than 250 km are consistent with the level of energy of the model on mapped nadir data, whereas SWOT-mapped observations enable the reconstruction of scales less than 100 km. The SWOT-mapped SSH spectrum follows quite faithfully the one from the true SSH until 85 km. The benefit of the interferometer compared to the constellation of two nadir altimeters is illustrated by the span of the arrow in Fig. 7a. The resolution of mapped SWOT SSH is 3 times better than the resolution of nadir-mapped SWOT. The loss of resolution between the mapped SWOT SSH and the SSH along a SWOT swath is also striking. The span of the arrow (Fig. 7b) emphasizes the gap of resolution between the mapped SWOT SSH and the SSH along the SWOT swath that represents scales up to 50 km. Comparing the spectra from SWOT-like SSH and from filtered SWOT-like SSH, one can see that filtering the SSH along the swath slightly improves the resolution of the SSH field as the corresponding power spectrum follows the power spectrum of the true SSH until 40 km. The filtering methods applied to the SWOT-like SSH can still be improved to possibly resolve scales smaller than 40 km from the SWOT observations.

In this study, it is clear that the performance of SWOT at small scales is better than that of a constellation of two nadir altimeters. However, improving the reconstruction of small scales in the mapping is an issue as a great deal of resolution is lost in the optimal interpolation. Further investigation is thus necessary to benefit from the full...
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**5. Conclusions**

The SWOT mission is a unique opportunity to observe small mesoscale/submesoscale dynamics in two dimensions. However, extracting information from the data is not straightforward. In this article, a tool that simulates observation from the SWOT interferometer is presented. The analyses of the simulated SWOT observations have shown that a great deal of small-scale signal is lost if the noise is not filtered properly. Furthermore, the process of mapping the SSH must evolve with the arrival of the real SWOT data. As illustrated by the study, the effective resolution of the mapped SSH is much better with the SWOT observations than the nadir altimeter observations in this configuration. However, the dynamics at scales smaller than 85 km are not well represented in the mapped SSH derived from the SWOT observations. Using the simulator tool, synthetic SWOT observations can be generated to explore new processes such as the internal tides or the vertical velocities (Lapeyre and Klein 2006) can also be investigated using the synthetic SWOT observations. Finally, performing OSSEs is essential to testing methods of assimilating the future SWOT data. Realistic synthetic SWOT observations of the SSH are essential to conducting the OSSEs.

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