Abstract

Studying ocean tides with satellite altimetry has traditionally been difficult in coastal regions. The 1-day repeat of the Cal/Val phase of SWOT provides a unique dataset that can be exploited for tidal analysis. In this work, KaRIn data from the SWOT Cal/Val phase are analysed in two coastal regions to present a first look at the possibilities for tidal analysis from SWOT. The areas are: (1) Bristol Channel and (2) Great South Bay. When benchmarked against in situ measurements in these regions, substantial improvements over tide models, which typically report errors exceeding tens of centimetres and degrees, are seen. Specifically, the SWOT ocean products exhibit amplitude discrepancies ranging from 1.75 to 3 cm and phase lag discrepancies between 1.75 and 2.75 degrees when compared with in situ tide gauge data. These findings underscore the value of SWOT for tidal research in complex coastal regions.
Tides in complex coastal regions: early case studies
from wide-swath SWOT measurements

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Key Points:
• SWOT KaRIn data from the Cal/Val phase is used to derive M₂ tide in two complex coastal regions.
• Results demonstrate the spatial variability of amplitude and phase lag of coastal tides.
• SWOT KaRIn measurements are useful for evaluating tidal flats and tides in river mouths and estuaries.

Abstract
Studying ocean tides with satellite altimetry has traditionally been difficult in coastal regions. The 1-day repeat of the Cal/Val phase of SWOT provides a unique dataset that can be exploited for tidal analysis. In this work, KaRIn data from the SWOT Cal/Val phase are analysed in two coastal regions to present a first look at the possibilities for tidal analysis from SWOT. The areas are: (1) Bristol Channel and (2) Great South Bay. When benchmarked against in situ measurements in these regions, substantial improvements over tide models, which typically report errors exceeding tens of centimetres and degrees, are seen. Specifically, the SWOT ocean products exhibit amplitude discrepancies ranging from 1.75 to 3 cm and phase lag discrepancies between 1.75 and 2.75 degrees when compared with in situ tide gauge data. These findings underscore the value of SWOT for tidal research in complex coastal regions.

Plain Language Summary
Estimating ocean tides in the coastal region has challenged tide modellers for decades. The recently launched SWOT satellite provides the opportunity to derive estimations of ocean tides at unprecedented spatial scales thanks to the innovative wide-swath measurement principle, particularly in complex coastal regions. The mission’s Calibration and Validation (Cal/Val) phase is particularly interesting for tidal research, as the tide-favourable orbit allows for the derivation of the major tidal constituents with a relatively short time series of SWOT data. This manuscript evaluates the largest tidal constituent, the principal lunar M₂ tide, derived from SWOT’s Cal/Val phase within two complex coastal regions. Results within the Bristol Channel and the Great South Bay demonstrate unprecedented spatial variability in the amplitude and phase lag of the M₂ tide. Additionally, with respect to in situ measurements, SWOT-derived estimates resulted in reduced errors compared to global tide models in these complex coastal regions. The initial insights demonstrated several strengths and opportunities for using SWOT to im-

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prove tide models and new avenues of research with satellite measurements of tides, par-
1 Introduction

Ocean tides influence a variety of oceanic and geodetic applications, such as sea level
analyses, gravity field determination and flood forecasting. The need for accurate esti-
mation and understanding of ocean tides for the removal of tidal signals in such appli-
cations has resulted in significant efforts to produce accurate tide models at both regional
and global scales (Ray, 1999; Egbert & Erofeeva, 2002; Cheng & Andersen, 2017; Lyard
et al., 2021; Hart-Davis et al., 2021). Ocean tide modelling has reached impressive lev-
els of accuracy in the open oceans, but challenges remain in the near coastal regions (Stammer
et al., 2014).

In recent years, satellite altimetry processing techniques have resulted in more re-
liable retrievals of sea level closer to the coast, with improved waveform retracking ap-
proaches allowing the retrieval of observations up to 3 km from land (Passaro et al., 2014).
Additionally, the TOPEX/Jason/Sentinel-6 series of altimeters, which serves as a back-
bone of tidal research, provides over thirty years worth of data and has been successfully
coupled with several missions on different orbits to improve tide model accuracy (Hart-
davis et al., 2023). In the coastal zone, novel processing techniques like Fully Focused
Synthetic Aperture Radar (FFSAR) (Egido & Smith, 2017; Schlembach et al., 2023) en-
hance the along-track resolution of satellite altimetry to meter-scale. However, conven-
tional and SAR nadir altimetry is still inherently limited by the wide separation between
satellite ground tracks. This spatial resolution is inadequate in the near-coastal zone ow-
ing to the dynamics of ocean tides in shallow water where non-linear distortions affect
the tidal wave and induce the growth of higher-order harmonics (Brown et al., 2023).
As a result, tides in the coastal region are larger and more spatially variable than those
found in the open ocean, with ranges exceeding ten meters in certain regions such as the
Bay of Fundy and the Bristol Channel.

Data from the Calibration and Validation (Cal/Val) phase of the Surface Water
and Ocean Topography (SWOT) satellite (Fu et al., 2024) provide the potential to mea-
Sure the spatial characteristics of the major tidal constituents at scales previously un-
known. The orbit of SWOT was designed in part to help improve the mapping of ocean
tides by avoiding aliasing major constituents into the mean sea level or the seasonal cy-
cle; however, some long alias periods are unavoidable for any satellite reaching into the
high latitudes.

This paper provides an initial assessment of the KaRIn data for tidal estimation
in complex coastal regions which are not well-represented in modern-day data-driven tide
models. We are aware that present SWOT measurements may suffer from some remain-
ing errors in data processing, especially in attitude determination (mostly from roll er-
rors). With this in mind, we focus here solely on the $M_2$ tide as it is the largest tidal con-
stituent and will, therefore, be less impacted by errors within the data. As SWOT col-
lects more data and corrections for dominant error sources are enhanced, future work
will provide more complete and precise estimations of all ocean tides.

In Sections 3–4, we discuss two case studies, one within the Bristol Channel on the
western coast of the United Kingdom and the second within Great South Bay on the east
coast of North America. Both highlight the value of SWOT for tidal research and the
limitations of current global tide models. While we employ primarily SWOT ocean data,
Section 5 briefly discusses using the SWOT hydrological high-rate pixel cloud product
for tidal research. Section 6 states conclusions and a short recommendation for the fu-
ture study of tides from SWOT.
2 Data and Methodology

Multiple versions of SWOT datasets are available from the Cal/Val phase. In this paper, the 250-m ocean product (available at: https://doi.org/10.24400/527896/a01-2023.016), the 2-km ocean product (“SWOT_L2_KaRIn_SSH_Unsmoothed” available at: https://doi.org/10.24400/527896/a01-2023.015, SWOT Project, 2023) and the high-rate pixel cloud data from the SWOT hydrological product (available at: https://doi.org/10.5067/SWOT-PIXC-299.0, SWOT, 2023) were used. From these data, all available data for passes #009 and #016 of the Cal/Val phase are extracted based on the two regions of interest. Only tiles ‘063R’ and ‘064R’ are extracted for pass #016 of the pixel cloud data for eighteen days based on data availability at the time of manuscript writing. The sea-level anomaly (SLA) is derived using the default geophysical corrections within the products with respect to the CNES mean sea surface, with the ocean tide correction withheld. The roll correction is applied in the ocean products, with no roll correction available at the time of writing for the high-rate pixel cloud Cal/Val data.

Within both regions analysed in this study, the Bristol Channel and Great South Bay, in situ measurements are used for comparison with SWOT. Tide gauge data is obtained from TICON-3 (Hart-Davis et al., 2022) for both regions, while local gauges deployed explicitly for the Cal/Val phase of the SWOT mission are obtained for the Bristol Channel (Lichtmann pers coms). Additionally, nadir satellite altimetry is also used for comparisons to highlight the value of the spatial picture provided by the SWOT data. These high-frequency altimetry data are of ENVISAT obtained from OpenADB (Schwatke et al., 2023) and an FFSAR track processed from Sentinel-3B (S3B). The FFSAR data are processed using the Standalone Multi-mission Altimetry Processor (SMAP; https://github.com/cls-obsnadir-dev/SMAP-FFSAR, www.satoc.eu/projects/ffsar). For the Bristol Channel track, 55 cycles of S3B data were processed at a posting rate of 1000 Hz, corresponding to an along-track resolution of 6 meters. Subsequently, the FFSAR waveforms were retracted using the Multiple Waveform Persistent Peak (MWaPP) re-tracker (Villadsen et al., 2016), and all range and geophysical corrections were applied (Andersen & Scharroo, 2011), except for the ocean tide correction.

The Cal/Val phase of SWOT provides a near-daily repeat, which, importantly, is non-sun-synchronous (the precise repeat period is 0.99349 days). With this sampling, the M₂ tide is aliased to a period of 12.4 days. Thus, although the Cal/Val campaign of 102 days is relatively short for tidal analysis of an aliased signal, it provides observations of eight full cycles of the aliased M₂. Several of the other major tidal constituents and several minor and nonlinear tides have alias periods that fall well below the 102 days of observation. Of most relevance here is O₁, with an alias period of 13.0 days, which is close to the M₂ alias and could thus impact M₂ estimation; nominally, 260 days are required to separate them. However, in both Bristol Channel and Great South Bay, in situ measurements indicate that O₁ is only a small fraction of M₂: it is roughly six times smaller than M₂ in Great South Bay and nearly 50 times smaller in Bristol Channel. Thus, its possible cross-correlation impact on M₂ can be expected to be minimal.

Owing to data gaps in the 102-day period, only 87 satellite observations were available at each SWOT location for the respective ocean products and only 18 days for the hydrological product. This small input time series places limitations on tidal analysis. We nonetheless used standard methods of harmonic analysis (e.g., Pugh & Woodworth, 2014), solving for seven semidiurnal tides and two compound tides. However, in light of the dominance of semidiurnal tides in our two regions, we ignored diurnal tides. As noted above, only M₂ is examined here in detail.
3 Bristol Channel

The Bristol Channel is a large, narrow inlet found on the southwestern coastline of Great Britain (Figure 1A), characterised by a gentle topographic slope and a deeper trench running through its centre. The physical characteristics of the channel give rise to both large ranges and nonlinear tidal waves (Phillips & Crisp, 2010). The semi-diurnal constituents are the main drivers of the tidal range within the estuary (Hashemi et al., 2008), making it a suitable region for exploiting the Cal/Val phase of SWOT for the M$_2$ tide.

The large tidal range, known to exceed 15 meters (Uncles, 2010; Phillips & Crisp, 2010), can be well identified within the SWOT data as shown in Figure 1D, with the mean channel SLA showing tidal ranges of more than 10 meters observed between low and high tide periods. A clear sinusoid of approximately 12 to 13 days can be seen, which, as mentioned earlier, is the approximate aliasing period of M$_2$ from SWOT, demonstrating a dominant contribution of M$_2$ to the variability of the Bristol Channel. Figures 1B and C show two snapshots of the lowest low and highest high tide from the KaRIn 250 meter product. In the low tide period, the SLA is contaminated around the edge of the channel and near location (2.9°W, 51.5°N) due to the exposure of the bottom topography or tidal flats at low tides (Carling et al., 2006), seen in the circles of Figure 1B. These tidal flats are not visible within the SLA observations in the high tide period. The presence of these tidal flats within the SWOT data presents another opportunity for study. For tidal research, however, these tidal flats will significantly influence the estimation of tides within the Severn Estuary and in other regions.

Figure 1. (A) The region of interest shown in the red square. (B) A low tide snapshot of SWOT SLA data, with circles highlighting tidal flats and (C) a high tide snapshot. (D) is the cross Channel SLA mean, with labels B and C corresponding to the above snapshots.

In the following results, the presence of the tidal flats within the SLA is not dealt with, partly to demonstrate their impact on tidal predictions but also due to the lack of a correction to account for this at the time of writing. Figure 2 presents the amplitude and phase lag estimations of the M$_2$ tide derived from the 250m, 2km and pixel cloud products of SWOT, as well as in situ measurements and an S3B pass.
The number of passes of the 250 m and 2 km products are the same, while significantly less data is available from the pixel cloud data. The S3B pass is an innovation for tidal research itself as it is derived from FFSAR, which, at the time of publication, is not available globally. What is evident within both amplitude estimations is reduced amplitudes caused by the influence of the observed tidal flats on the estimations made by all of the SWOT products. Additionally, they all show an increase in amplitude and phase lag from west to east, consistent with the region’s tide gauge measurements.

With respect to the in situ measurements of the $M_2$ tide within the region, estimations done by the SWOT 2 km product vary by an average of 2.58 cm and 2.72 degrees for the amplitude and phase lag estimation, respectively. The difficulty of validation to in situ gauges with the 250 m product and the pixel cloud data is demonstrated.
in Figure 3, where a zoom is done around Hinkley Point on the south side of the domain of interest, demonstrating the small variability seen. This is related to the bottoming out of the channel in periods of extremely low tides, which play a role in the amplitude and phase determination of the tides.

This can additionally be seen in Figure 2, where a well-known tidal flat can be observed within the tidal estimation at around 51.5°N and 2.95°W. This strength of SWOT in providing a realistic spatial view of the region poses an additional challenge to tidal research as these flats or exposed bottom topography periods should be appropriately processed to get a realistic tidal estimation. When validating tidal estimates from models or along-track data, the usual practice would be to either take the nearest point or do a linear interpolation of the results. In this case and others, it is evident that doing so would result in large amplitude and phase lag errors. One might expect the tide gauges themselves to also experience these ‘bottoming’ out periods, but based on the evaluation of the tide gauge time series, this was not deemed the case (not shown).

This is certainly due to the measuring technique of the gauges, with Hinkley Point being located in underwater vented chambers (Phillips & Crisp, 2010), for example. However, when implementing a rather simplistic method of taking the estimations further away from these tidal flats, the mean amplitude and phase lag error are 2.72 cm and 4.03 degrees, respectively, for the 250m product. These initial SWOT results are impressive, especially considering the challenges models and traditional altimetry have had in this region; see below.

Using a relatively modern FFSAR approach, the median amplitude and phase lag difference between the S3B data and the SWOT 250m (2km) product is 5.89 (11.14) cm and 5.25 (2.08) degrees, respectively. As mentioned previously, only 55 cycles worth of S3B data are used here, which is limited for estimations of tides and may be improved with an increased time series. Despite the enhanced along-track resolution, the S3B data are still susceptible to snagging-related issues caused by waveform contamination by off-nadir returns, evident in the northern section of the Bristol Channel near the sand bank.

To further assess the value of SWOT for tidal research, two state-of-the-art tide models, EOT-NECS (Hart-Davis et al., 2023) and FES2014b (Lyard et al., 2021), are contrasted in this region. These two models provide highly accurate estimations for the greater UK and European coastal areas, but both models operate at a spatial resolution, 1/16°, that is insufficient to capture the variability of the Bristol Channel. A common approach for using tide models as altimetry corrections is to apply linear interpolation to the models to extract tidal information in such complex coastal regions. In some instances, especially taking into account the limited data availability, this approach is justified to provide a viable solution. In this instance, linear interpolation of the models onto the locations of the 250 m SWOT product reveals deficiencies. In Figure A1 of the supplementary material, it can be seen that in terms of amplitude, both models comfortably exceed 10 cm differences throughout the region, with some places exceeding 20 cm differences. These differences are not surprising due to the limited altimetry coverage in this region. However, this provides further motivation for high-resolution SWOT data to be incorporated within the next generation of global data-driven models.

Overall, for the Bristol Channel, the results derived from SWOT demonstrate that it is clearly possible to retrieve accurate estimations of tidal constituents and that the spatial variability provided is clearly increasing our previous knowledge of tides in the region. Additionally, several avenues have been identified which would benefit both SWOT and the tidal community, such as the monitoring and accounting for tidal flats within the SWOT data.
The Great South Bay presents a different challenge for tide modelling efforts. The bay is located on the east coast of the United States and is extremely shallow (no deeper than 10 meters) and is separated from deeper waters by Fire Island (Figure 4). This barrier between the bay and the open ocean impacts the phase lag and amplitudes of tidal constituents within the bay. Unlike the Bristol Channel, the tidal range of this region is relatively small, which, when coupled with the known large variation in tidal characteristics inside and outside the bay, highlights the usefulness of SWOT for mapping small-scale coastal tides.

Results of harmonic analysis are presented for the M\textsubscript{2} within Figure 4B and C and contrasted to results from ENVISAT along-track data obtained from OpenADB (Schwatke et al., 2023). The amplitude and phase lag estimations, as also seen by the ENVISAT nadir altimeter, reveal the spatial variations caused by the Fire Island barrier on the tidal structure inside and outside the bay. The amplitude drops by about 50 cm from outside to inside the bay, with the phase lag varying by about 120 degrees. All of the in situ measurements in this region are inside the bay, and SWOT-derived constituents show mean amplitude and phase lag differences of 1.75 cm and 3.36 degrees, respectively. This is considerably lower than global tide models, with EOT20 (Hart-Davis et al., 2021) and FES2014 showing differences with respect to the same tide gauges of 17.97 cm and 22.12 cm for amplitudes and 72.19 and 55.42 for phase lag, respectively. When we take into account the spatial resolution of both these global models, it is clear that they cannot capture the amplitude and phase lag shift seen within the bay.

Additionally, the altimetry data used for these models (for example, ENVISAT seen in Figure 4B and C) also do not provide estimations consistent with SWOT and are riddled with errors inside the bay. When assessing a regional hydrodynamic model, AD-CIRC (Szpilka et al., 2016), which has a much higher spatial resolution than the global models evaluated previously, this amplitude and phase lag variation is captured, as demon-
Figure 4. (A.) SLA from pass #009 and cycle #478 of SWOT across the east coast of the United States of America, with a box highlighting the region of interest. M\textsubscript{2} amplitude (B) and phase lag (C) derived in the Long Island region from the 250m product. Tide gauges are represented by stars, and tides derived from an ENVISAT pass are shown. (D) presents a cross-section of the resultant phase lag estimations at 73°W across the Great South Bay compared to available TICON-3 tide gauges, a global (FES2014) and regional tide model (ADCIRC).

strated in a transect of the phase lag at 73°W in Figure 4D. The open ocean south of Fire Island is well-mapped by historical altimetry. It is thus worth noting that the SWOT M\textsubscript{2} estimates there differ from FES2014 by only 1.2 cm root-mean-square error. Thus, any impact on M\textsubscript{2} estimation caused by the close alias periods of M\textsubscript{2} and O\textsubscript{1} appear in this region to be minimal.

The results in Great South Bay further demonstrate the value of SWOT for tidal research and the potential limitations of tidal corrections for SWOT in such complex regions. Additionally, as the amplitude is so small within the bay, the phase lag variations seen by SWOT and \textit{in situ} measurements within are equally interesting at scales previously not possible. Furthermore, although global models are reaching impressive levels of accuracy, the current method of validating with \textit{in situ} measurements that capture much finer variations in individual constituents may not be providing a complete story of the accuracy of tide models nearer to the coast. For example, the tide gauges presented here are used in the global validation of models and can negatively influence the mean statistics of error estimates by tens of cm and degrees. SWOT can fill this gap by providing greater insight as to why models differ from \textit{in situ} gauges and how appropriate particular gauges are to evaluate models at certain resolutions. Finally, the results presented here also highlight the value of continued effort on tidal estimations for and from SWOT. An investigator desiring to use SWOT for any sea level-related process within Great South Bay will encounter inaccurate results caused by unsuitable tidal corrections from current global models.

5 A note on the hydrological product

For certain locations, including coastal areas, SWOT provides pixel cloud data with a resolution of approximately 6 meters along-track and a cross-track resolution of 70 m
in the near swath to about 10 m in the far swath. This product allows for a high-resolution
representation of water level variability and dynamics for many applications, particu-
larly those of inland waters. In principle, such a high-resolution product is unnecessary
for ocean tide applications due to the limited spatial variability of ocean tides at such
scales, particularly further from the coasts. However, in complex coastal environments
such as regions with tidal flats, fjords, and estuaries, such resolution may allow for solv-
ing topography-related errors or describing tidal characteristics in very narrow regions.

At the time of publication, only 18 days of these data in the Cal/Val phase are avail-
able, which does not favour reliable retrieval of tidal estimations. However, when ignor-
ing potential cross-contamination from other tidal constituents, the $M_2$ constituent is
theoretically derivable. Based on this, a tentative look was done on the usability of the
pixel cloud data for tidal analysis in the Bristol Channel (Figure 2 C and D). It should
be emphasised that once more data is available, the resultant tidal estimations will be-
come more accurate and potential differences will be seen in the amplitude and phase
spatial structures. However, this discussion aims to highlight the usability of the pixel
cloud data for tidal research.

Figure 2 C and D presents the amplitude and phase lag of the $M_2$ derived from the
pixel cloud data. Despite the considerable time-series length differences, the pixel cloud
demonstrates similar amplitude and phase lag structures compared to the 250m prod-
uct (Figure 2). Clear artefacts exist within this data, particularly around 51.25°N and
3.25°W, which are seen in the water level time-series obtained from SWOT (Figure A2)
and would likely be removed with appropriate data processing and sufficient time-series
lengths. The evidence of the sand banks on the northeastern part of both plots is also
evident within this dataset, with much sharper representation owing to the increased spa-
tial resolution. The appropriate classification of these data will be critical to limiting er-
rors in tidal research moving forward.

These data have the potential to open the door to a great variety of tide applica-
tions not previously possible from conventional altimetry data. Particularly, the tidal
dynamics upstream of rivers (seen in Figure 2C and D) and their potential interactions
with rivers are interesting avenues from which SWOT can be exploited. These data will
also be valuable in assessing tides in fjords, where tides can play a significant role but
are not appropriately captured by modern-day global tide models.

6 Conclusions

This brief overview presents two case studies exploiting the newly released wide-
swath SWOT data obtained during the Cal/Val phase, which highlights SWOT’s unique
value for ocean tidal analysis, even while focusing solely on the $M_2$ tide due to the short
observation period. The study reveals that SWOT’s high spatial resolution and two-dimensional
coverage enable a detailed analysis of tides in complex coastal regions, surpassing the
capabilities of traditional nadir altimetry. However, this enhanced observational power
also brings new challenges to tidal research, particularly in the classification of intertidal
zones to prevent signal contamination and ensure accurate tidal estimations. Despite these
challenges, the advent of SWOT allows for improved coastal modelling detail, especially
in regions where data assimilation of tide gauges is impossible owing to a lack of useful
observations.

The task of deriving tides in complex coastal regions will begin in earnest as the
SWOT time series lengthens. This first look at SWOT capabilities in complex coastal
regions has highlighted the possible applications of these data for mapping small-scale
coastal tides. It is envisioned that future iterations of global models will take on new res-
olutions and provide increased coverage into rivers, estuaries and fjords.
Acknowledgments

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