Challenging SWOT: Early Assessment of Level 2 High-Rate River Products in an Urbanized, Low Elevation Coastal Zone

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***Abstract*— The surface water and ocean topography (SWOT) mission offers groundbreaking opportunities to observe fine-scale spatial changes in low elevation coastal zones (LECZs). This study explores the first SWOT data in one of the mission's most challenging environments: a data-scarce, tropical region with flat topography, heavy urbanization, and a river with a weak, tidally influenced slope. We focus on SWOT's water surface elevation (WSE) and water surface slope (WSS) products at the reach level, comparing the measurements to in situ data. Our analysis shows that about half of SWOT's WSE and WSS measurements fall within the desired error budgets, though WSS lacks linear correlation with in situ data. At this early stage, both SWOT's WSE and WSS require validation in such complex areas. However, as SWOT's high-resolution observations improve over time and are integrated with other data, they are expected to provide valuable insights into dynamic river and estuarine processes.**

***Index Terms*— Estuary, low elevation coastal zone (LECZ), surface water and ocean topography (SWOT), tidal river, water surface elevation (WSE), water surface slope (WSS).**

I. Introduction

GEOPHYSICAL processes in low elevation coastal zones (LECZs) are primarily governed by the interaction between river discharge and coastal ocean dynamics [1]. The southern region of Vietnam, particularly Ho Chi Minh City (HCMC), is a densely populated LECZ with up to 30 000 inhabitants per square kilometer in its urban center [2]. HCMC is characterized by its extensive water system, including the tidal Saigon River and around 800 km of canals. With 90% of its urban area impermeable, the city experiences significant hydrological impacts [3], leading to frequent flooding from both river overflow and rainfall runoff [4]. This issue is exacerbated by increasing extreme rainfall events, making HCMC one of the most vulnerable coastal regions globally [5]. Despite these challenges, the Saigon basin remains largely under monitored, hindering effective water resource management and extreme event prevention efforts in HCMC.

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Launched in December 2022, the surface water and ocean topography (SWOT) mission aims to transform our understanding of Earth's surface waters with high-resolution altimetric measurements of rivers, coastal regions, and oceans [6]. We hypothesize that SWOT data could enhance our knowledge of tidal river-estuary systems. This study explores the application of SWOT data for characterizing the Saigon River, a crucial waterway in HCMC's urban landscape. Despite its strategic importance, the Saigon River presents significant challenges for in situ monitoring due to its complex tidal regime and dense urbanization. SWOT data offer a promising approach to overcome these challenges, though radar interferometry faces difficulties due to flat topography, dense urbanization, and a river with a gentle water surface slope (WSS) influenced by strong coastal tidal forcing.

Here, we present an early assessment of SWOT level 2 high-rate river reach products namely, of water surface elevation (WSE) and WSS, over this region. We examine the accuracy and reliability of WSE and WSS, shedding light on their utility for future hydrological studies. Furthermore, we discuss the implications of our findings for leveraging SWOT data in data-scarce, tropical LECZs and enhancing our understanding of riverine processes in complex environmental settings.

II. Data and Methods

A. In Situ Measurements

Three measurement locations for WSE along the Saigon River are used: Hobo 2 (H2), Hobo 3 (H3), and La Garden (LG) [black crosses in Fig. 1(c)]. The location selection was constrained by on-site factors such as inaccessibility to the riverbank and challenges in sensor installation, with two main criteria: 1) comprehensive coverage of key sections of the Saigon River within the center of Ho Chi Minh City and 2) maintaining a distance of approximately 10 km between sensors to match the spatial resolution of SWOT reach products.

Measurements were obtained using Onset HOBO U20L-01 water level loggers, measuring absolute pressure every 15 min. These devices have a typical error of 1 cm, a maximum error of 2 cm, and a resolution of 0.2 cm. To ensure accuracy, measurements were barometrically compensated using air pressure data. Since the vertical reference points of the pressure sensors were different and unknown, all signals were normalized for comparison [7]. Given that tidal fluctuations dominate the WSE signals throughout the river, normalization

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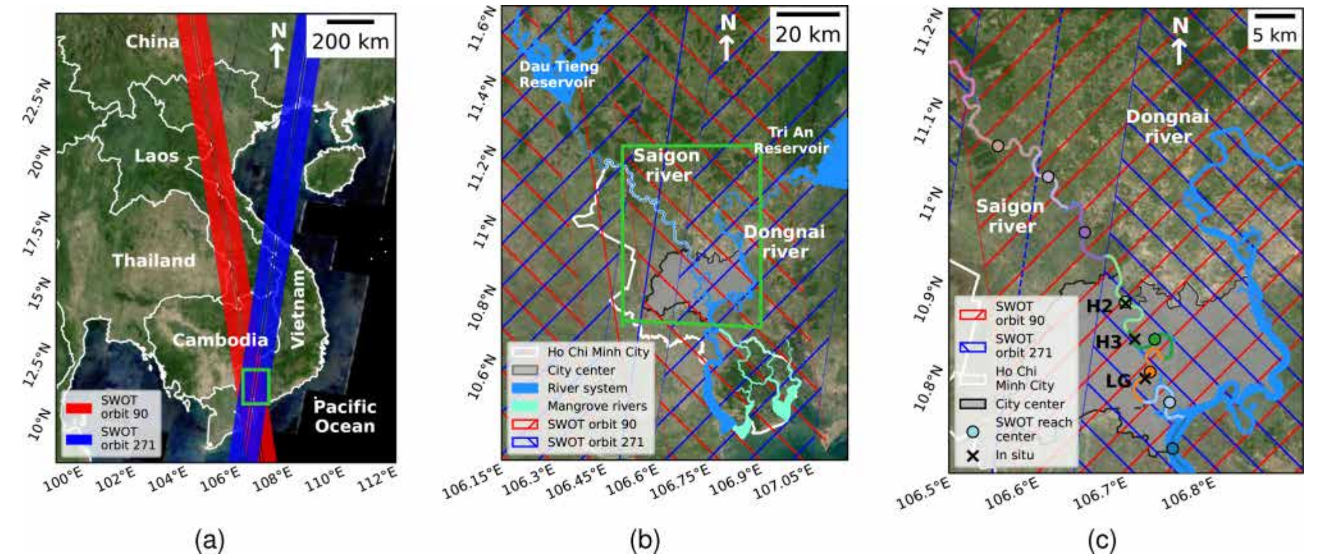

Fig. 1. (a) Overview of the region. The green box highlights the study area depicted in (b). (b) Map of the study area. The area within the green box corresponds to the city center area depicted in (c). (c) City center area, displaying WSE gauges used to validate SWOT measurements: H2, H3, and LG marked as black crosses. The SWOT reaches are illustrated in color, with the center of each reach indicated by a colored dot.

allowed for direct comparison between sensors by having all signals fluctuate around zero. Additionally, to compare the normalized in situ measurements with SWOT data, the former were adjusted by 1.5 m to match SWOT's reference geoid (EGM2008) corrected for tide effects [8].

From the WSE measurements, the WSS between two sensors is computed as the difference between two measurement locations divided by the along-river distance between them.

B. SWOT Mission and River Reach Products

SWOT provides observations for 10 km river reaches [see colored Saigon river reaches in Fig. 1(c)] and nodes spaced about 200 m apart. These measurement locations, predetermined before launch, are cataloged in the SWOT river database (SWORD) [9]. For most rivers, SWOT is expected to achieve a minimum error of 10 cm in WSE and 1.7 cm/km in WSS [10].

The Saigon River is observed by two SWOT orbits: 90 and 271 [Fig. 1(a) red and blue, respectively], receiving observations on day 4 (orbit 90) and day 10 (orbit 271) within each 21-day cycle. These orbits collectively cover the entire river [Fig. 1(b)] at least once per cycle. SWOT observations are spatially heterogeneous due to nadir gaps in both orbits. From the upstream Dau Tieng reservoir [Fig. 1(b), upper left corner), the first 56 km are observed on day 10 [blue orbit 271 in Fig. 1(b)]; the section from 56 to 94 km is observed on day 4 [red orbit 90 in Fig. 1(b)]; and the remaining section from km 94 to the confluence with the Dongnai River is monitored on both day 4 and day 10. In this study, we evaluate three of the SWOT reaches that overlap with our in situ locations [presented in orange, green and aquamarine in Fig. 1(c)].

Only data from SWOT's cycle 10 onward is available for analysis as previous cycles did not include measurements over this region. In this letter, we present the SWOT Level 2 River Single-Pass Vector Reach Data Product (Version 2.0). This dataset provides measurements of WSE and slope derived from the high rate data stream from the KaRIn instrument. The associated uncertainty is automatically computed by the SWOT mission team. SWOT uncertainty estimation is a function of the quality of the measured pixels from the KaRIn instrument. Pixel-cloud information is aggregated into node-level data which in turn is averaged over a reach to provide the reach data product [11]. Pixel quality flags are provided by the SWOT team and take the values of good, suspect, degraded, or bad. The data are sourced from the Physical Oceanography Distributed Active Archive Center (PODAAC) [12] and is freely accessible to the community.

III. Results

Fig. 2 shows WSE time-series for three in situ locations across different SWOT cycles. Each plot features SWOT measurements and estimated uncertainty for pass 90 and pass 271, except cycle 15 which only includes pass 271. SWOT measurements are depicted as dots with uncertainty bars: blue for those within the 10 cm error budget [10], and red for those exceeding it. Measurements exceeding the error budget show errors ranging from 0.12 to 7.99 m, as detailed in Table I.

To investigate the causes of these errors, we analyze the dark water fraction (DWF) and the ratio of valid nodes (RVNs) to total nodes within a SWOT reach. Table I presents the absolute error, DWF, and RVN for each cycle-pass pair and location. Of the 33 SWOT measurements, 14 fall within the 10 cm error budget (highlighted in blue). For these measurements, RVN ranges from 66% to 96%. However, even measurements exceeding the error budget can show high RVN values. For example, cycle 12, pass 271 has an error of 37 cm despite an RVN of 100%. This suggests that a high RVN may not always reflect measurement accuracy, as the overall error can still exceed the budget even when all nodes are valid.

In Table I, the middle column shows the fraction of dark water pixels within a reach. We find that few SWOT measurements have a high fraction of dark water pixels. The two largest errors (Cycle 11, pass 271, and Cycle 12, pass 271) have no dark water pixels detected by SWOT, indicating that

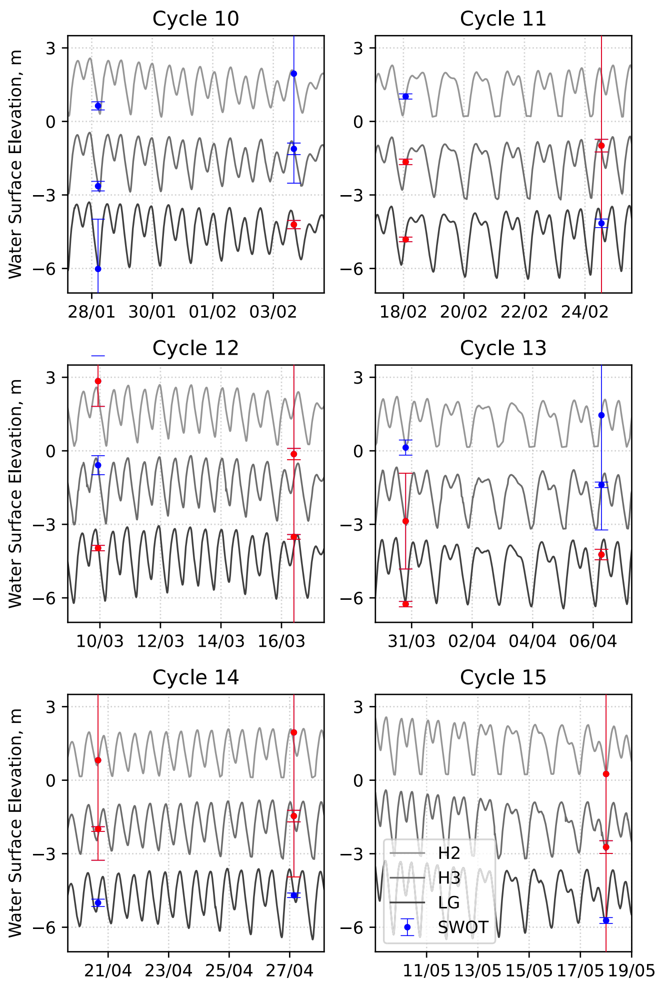

Fig. 2. Timeseries of WSE at the three in situ locations H2, H3, and LG. The signals are displaced by 3.5 m. The two SWOT measurements per cycle (pass 90 and pass 271) are presented as dots with uncertainty bar. SWOT measurements within and outside of the error budget of 10 cm are presented in blue and red, respectively. Note that some inaccurate SWOT data fall outside of the area of the plot.

TABLE I

SWOT WSE Error (in m, Left Column), DWF (in %, Middle Column), and RVN (in %, Right Column) for Each In Situ Location [H2, H3, and LG in Fig. 1(c)]. SWOT Measurements That Meet the Error Budget Are Highlighted in Blue

Cycle	Pass	H2			H3			LG		
10	90	0.01	0	87	0.01	1	79	0.06	3	68
10	271	0.01	0	72	0.08	5	79	0.17	1	87
11	90	0.05	11	96	0.25	18	92	0.21	37	98
11	271	7.95	0	37	0.16	0	79	0.04	1	89
12	90	0.48	63	55	0.08	47	66	0.14	14	91
12	271	7.99	0	38	0.96	0	77	0.37	0	100
13	90	0.06	6	85	0.12	19	62	0.14	12	94
13	271	0.07	0	76	0.01	0	91	0.33	0	87
14	90	0.13	1	69	0.28	4	98	0.05	1	89
14	271	0.49	0	73	0.21	0	79	0.01	4	98
15	271	0.14	4	52	0.13	7	79	0.08	14	92

measurement quality is not significantly impacted by dark water-related issues in these cases.

In Fig. 3, in situ WSE measurements are plotted against SWOT WSE measurements at three locations with a linear regression. Although only 14 out of 33 SWOT measurements

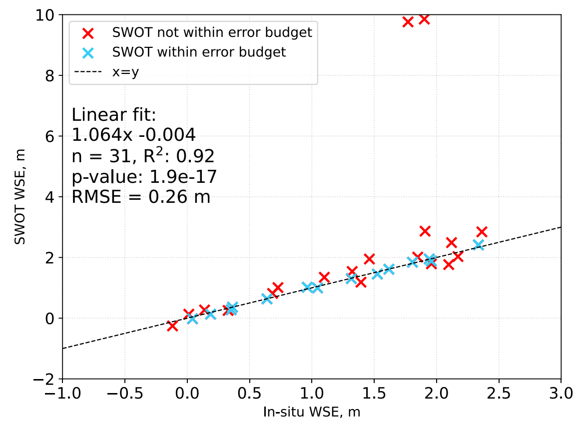

Fig. 3. Comparison between in situ and SWOT WSE.

fall within the error budget, we see a strong linear correlation between SWOT and in situ WSE, with an R^2 of 0.92 and a near-zero p-value. The RMSE of 0.26 m, though over the budget, is still acceptable, which is promising for the region as SWOT measurements are likely to improve over time.

A similar analysis was done for WSS products (from Bayesian reconstruction algorithm, see supplemental material). Half of the 24 SWOT WSS measurements fall within the error budget, with RVN values ranging from 52% to 98%. For those outside the budget, errors range from 1.97 to 64 cm/km. There was no linear correlation between SWOT WSS and in situ, with an RMSE of 19.8 cm/km—about an order of magnitude higher than Saigon's WSS.

In order to explore possible causes of SWOT errors, the raised pixel-cloud quality flags can offer valuable insights. In this study, the most commonly occurring pixel-cloud quality flags [13] are as follows.

1) *Classification Suspect Flag:* Land/water classification information from the pixel-cloud is marked suspicious.
2) *Geolocation Suspect Flag:* Pixel-cloud geolocation information is marked suspect.
3) *Water Fraction Suspect Flag:* Water-fraction information from the pixel-cloud is suspiciously large.
4) *Geolocation Degraded Flag:* Pixel-cloud geolocation information is marked degraded. These are discussed in Section IV.

IV. Discussion

In this letter, we analyze SWOT Level 2 high-rate river products in a tidal river, focusing on WSE and WSS. Our findings indicate that both data require ground truth validation as estimated uncertainties can be misleading (see error bars in Fig. 2). This highlights the critical role of in situ data for effectively using SWOT measurements in challenging environments. We observe that uncertainty bars for pass 271 are often larger than those for pass 90. These uncertainty estimates depend on various factors, including proximity to the nadir point [14]. Since pass 271 intersects the Saigon River along the nadir track, locations like H2 are closer to the nadir gap than during pass 90 [see blue nadir track in Fig. 1(c)].

This proximity accounts for the high estimated uncertainty in measurements that still meet the error budget.

Less than half (14 out of 33) of the analyzed SWOT WSE data met the error budget of 10 cm. Similarly, for WSS retrieved by SWOT, only half were within the error budget of 1.7 cm/km. We found that the RVNs for a given reach is not a reliable proxy for trusting a SWOT measurement; while good measurements often have RVN values above 66%, poor measurements can also arise from reaches with high RVN values.

SWOT errors depend on the quality of the pixels measured by the KaRIn instrument and used for WSE and WSS computations. The classification information from the pixel-cloud captured by SWOT distinguishes water pixels from land pixels [13]. These data are used to aggregate high-resolution pixel-cloud data to known river features from the prior river database [9]. Once the pixels are assigned, ensemble measurement quantities for each river feature are computed from the assigned pixels. The pixel-cloud data are first aggregated to the node locations, and then the node attributes are further aggregated to generate the reach attributes [13]. The reach attributes, which are the data used in this study, are expected to meet the 10 cm error budget. However, as discussed in Section III, SWOT presents errors above this budget of which three main quality flags were raised: classification, geolocation, and water fraction flags.

The classification flag relates to the number of pixels classified as water versus land. This flag could be attributed to the Saigon River's role as a major commercial navigation route, accommodating ships with drafts up to 9 m [15]. Constant large container ship traffic, along with boat habitation [16], may contribute to the difficulties SWOT faces in obtaining WSE measurements. Additionally, the river is heavily populated with water hyacinths that are visible from space [17] and cover large areas of the water surface. Furthermore, slums, particularly those on stilts over the river and canals in the urban center [18], [19], could further complicate SWOT's ability to distinguish between water and land pixels.

The classification flag is related to the DWF within a reach (Table I). Dark water can cause errors in SWOT measurements due to lower radar backscatter, which weakens the signal-to-noise ratio needed for accurate detection. This often occurs when the water surface is very smooth under low wind conditions [20], leading to specular reflection that causes radar signals to bounce away from the instrument, making the water appear dark. As a result, SWOT may misclassify or entirely miss the water, leading to measurement errors. However, only a small portion of measurements exhibit a high DWF and significant errors are not necessarily linked to high DWFs, as shown in Table I.

The geolocation flag pertains to the geolocation accuracy of the pixels identified as water. Geolocation problems can arise from phase unwrapping which is the process of resolving ambiguities in radar phase measurements, allowing for the accurate retrieval of continuous WSEs from the radar signals [21]. We found evidence of phase unwrapping errors impacting SWOT measurements, particularly at the H2 location for pass 271 (see supplemental material for an illustration of this problem). The proximity of the H2 location to the nadir, combined with the urban environment, increases the likelihood of phase unwrapping issues.

Upon examining the 100 m raster and pixel cloud products from SWOT, we found that in the H2 area, the river is sometimes displaced by approximately 700 m at the boundary between two pixel-cloud tiles. This displacement likely accounts for the large errors observed, particularly in pass 271. Additionally, this issue may be related to the over-detection of water, which raises the water fraction flag. This flag is raised when the fraction of water within a pixel exceeds acceptable limits. The urban surroundings of the Saigon river are highly impermeable, and rainwater can remain for extended periods, potentially causing flooding [4]. Additionally, human-made canals around it are ubiquitous. These static and ephemeral water surfaces can reduce the quality of the measurements and trigger this type of problem.

Another possible reason for the displacement of the river at the H2 location is the layover effect between land and water pixels. The example given in [6] illustrates rather well the layover effect: suppose that a hill located a few kilometers away from a river might have a distance to the satellite similar to that of the river's center, and thus appear close to the river center in a SWOT image. In contrast, the river banks, being at a different distance from the satellite, could appear several pixels away from the river center pixel. As a result, the top of the hill could be closer to the river center than the river banks. The layover phenomenon is well-known and has been extensively studied [10].

The region under study is part of an extremely flat, LECZ, with 65% of Ho Chi Minh City located at less than 1.5 m above sea level [4]. Indeed, SWOT uncertainty is greatest in flatter areas rather than in regions with complex topography [22]. This is primarily due to the layover from topographic features, such as skyscrapers and vegetation around and in the river [6]. Additionally, the layover effect has a greater impact on river slope measurements than on river height, partly explaining the poorer results for SWOT WSS found in this study. The Saigon River's slope fluctuates between -6 and $+6$ cm/km due to coastal tidal forces. As a result, the magnitude of the SWOT WSS uncertainty is comparable to the measured slope, increasing the potential for large errors illustrating the need of validation against in situ in such environments.

WSE and WSS are two hydraulic variables essential for river discharge computation and are crucial for assessing a river system. As presented in this letter, SWOT's capability to observe these variables in a very flat, tropical, urbanized coastal area is overall positive, as this environment may be the most challenging for any satellite altimetry mission. However, to fully use SWOT data, it is also important to consider how sampling frequency impacts the derived hydraulic variables at a given site [23]. In the Saigon River, SWOT's temporal frequency is about three measurements per month due to its low latitude and North–South extent, presenting a further challenge to the usability of SWOT data for hydrological studies in the area. Nonetheless, SWOT's unprecedented spatial resolution can still provide valuable insights into the river's behavior.

This advantage can potentially be used to better calibrate and validate hydraulic models once more SWOT data are available [24].

In data-scarce regions like this one, in situ data remain crucial despite SWOT's capabilities. SWOT's temporal resolution constraints make it an additional tool rather than a replacement, providing valuable data to complement in situ data and hydraulic models. As the SWOT mission progresses and more data become available, the quality of SWOT products will improve and are thus, posed to become an increasingly valuable resource for enhancing discharge estimates for the Saigon River [7].

V. Conclusion

In this study, we analyze SWOT WSE and WSS products in a challenging region characterized by flat topography, a tropical urban environment, and a river with a weak slope influenced by strong coastal tidal forces. Our analysis reveals that only about half of the WSE and WSS measurements meet the error budget and both require in situ validation for reliability. Additionally, we identified phase unwrapping and layover as significant sources of error at river locations near the nadir gap.

This letter provides an early assessment of SWOT's potential in such coastal environments. We expect that SWOT's high-resolution 2-D observations will improve over time, and together with field data, other satellite data, and modeling efforts, will yield new insights into dynamic phenomena in this and similar coastal zones.

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