



**Swath altimetry measurements of the mainstem Amazon River**

M. D. Wilson et al.

# Swath altimetry measurements of the mainstem Amazon River: measurement errors and hydraulic implications

M. D. Wilson<sup>1</sup>, M. Durand<sup>2</sup>, H. C. Jung<sup>3</sup>, and D. Alsdorf<sup>2</sup>

<sup>1</sup>Department of Geography, University of the West Indies, St. Augustine, Trinidad and Tobago

<sup>2</sup>Byrd Polar Research Center and School of Earth Sciences, Ohio State University, 125 S Oval Mall, Columbus, OH 43210, USA

<sup>3</sup>Hydrological Sciences Laboratory, NASA Goddard Space Flight Center, 8800 Greenbelt Rd, Greenbelt, MD 20771, USA

Received: 22 June 2014 – Accepted: 25 July 2014 – Published: 6 August 2014

Correspondence to: M. D. Wilson (matthew.wilson@sta.uwi.edu)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Abstract

The Surface Water and Ocean Topography (SWOT) mission, scheduled for launch in 2020, will provide a step-change improvement in the measurement of terrestrial surface water storage and dynamics. In particular, it will provide the first, routine two-dimensional measurements of water surface elevations. In this paper, we aimed to (i) characterize and illustrate in two-dimensions the errors which may be found in SWOT swath measurements of terrestrial surface water, (ii) simulate the spatio-temporal sampling scheme of SWOT for the Amazon, and (iii) assess the impact of each of these on estimates of water surface slope and river discharge which may be obtained from SWOT imagery. We based our analysis on a “virtual mission” for a 300 km reach of the central Amazon (Solimões) River at its confluence with the Purus River, using a hydraulic model to provide water surface elevations according to SWOT spatio-temporal sampling to which errors were added based on a two-dimension height error spectrum derived from the SWOT design requirements. We thereby obtained water surface elevation measurements for the Amazon mainstem as may be observed by SWOT. Using these measurements, we derived estimates of river slope and discharge and compared them to those obtained directly from the hydraulic model. We found that cross-channel and along-reach averaging of SWOT measurements using reach lengths of greater than 4 km for the Solimões and 7.5 km for Purus reduced the effect of systematic height errors, enabling discharge to be reproduced accurately from the water height, assuming known bathymetry and friction. Using cross-section averaging and 20 km reach lengths, results show Nash–Sutcliffe model efficiency values of 0.99 for the Solimões and 0.88 for the Purus, with 2.6 and 19.1 % average overall error in discharge, respectively.

## HESSD

11, 9399–9434, 2014

### Swath altimetry measurements of the mainstem Amazon River

M. D. Wilson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



# 1 Introduction

The hydrological cycle is of fundamental importance to life and society and river gauges have long formed a basis our hydrological understanding, often providing real-time measurement capabilities of river stage or discharge and information for water management and flood warning. Yet existing in-situ gauge networks are unevenly distributed globally, with a distinct lack of measurements obtained in developing countries, particularly for areas with low population (Vorosmarty et al., 2001; Shiklomanov et al., 2002). In addition, gauging stations are highly variable in their accuracy and are under threat. The US has around 7000 stream gauges but, even so, more than 20% of basins are not gauged adequately (USGS, 1998), contributing to an insufficient knowledge of available national water resources (NSTC, 2004). Over the latter half of the 20th century, increasing numbers of gauging stations in the US with 30 or more years of record were discontinued each year; in the mid-1990s, this represented about 4% of the long-record stations being discontinued (USGS, 1998). The situation globally is substantially worse than in the US, with much of the globally significant discharge occurring in sparsely gauged catchments (Alsdorf et al., 2003). The gauge density in the Amazon, expressed as number of gauges per unit discharge, is around 4 orders of magnitude less than what is typical in the eastern US (Alsdorf et al., 2007b). World-wide, Fekete and Vörösmarty (2007) indicate that the amount of data available through the Global Runoff Data Centre (GRDC) is in sharp decline, and now stands at less than 600 discharge monitoring stations, down from a peak of around 5000 in 1980. Remote sensing has a potentially useful role to play to fill the gaps in river gauge data, with the added benefit of being able to reduce data access issues in international river basins, which contribute to greater than 50% of global surface flows (Wolf et al., 1999) and where obtaining information about upstream flows can be politically challenging (e.g. Hossain et al., 2007).

Remote sensing has been shown to be a valuable addition to ground-based gauges with satellite altimetry, in particular, used extensively to obtain water elevations of inland

## HESSD

11, 9399–9434, 2014

### Swath altimetry measurements of the mainstem Amazon River

M. D. Wilson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





rivers with higher temporal variability or during periods of highly variable flow, such as flood events.

These limitations mean that, for the majority of rivers, satellite altimetry does not provide sufficient detail to capture the full spatial or temporal complexity of river hydrology. In addition, profiling altimetry has been shown to miss entirely 32% rivers globally, compared to only 1% of rivers being missed by an imager (Alsdorf et al., 2007b). In common with river gauges, measurements obtained by profiling altimetry are spatially one-dimensional, meaning that no information on water surface area or two-dimensional patterns in water surface slope are provided. However, SAR interferometry work by Alsdorf et al. (2007a) has shown that water flow is both spatially and temporally complex, requiring two-dimensional, multi-temporal measurements to capture sufficiently. This means that our current, operational remote sensing has a limited capability for an important component of the water surface (Alsdorf et al., 2007b). Remote sensing has been used with some success to characterize hydraulic variables including surface water area and elevation, water slope and temporal changes, but none of the existing technologies is able to provide each commensurately, as needed to model accurately the water cycle (Alsdorf et al., 2007b).

The forthcoming Surface Water and Ocean Topography (SWOT) mission (Durand et al., 2010) aims to overcome existing limitations in remote sensing by using a swath altimetry approach to measure surface water elevation in two-dimensions, providing both surface water area and elevation simultaneously. Such measurements may allow water surface slopes to be derived instantaneously and, therefore, potentially could provide estimates of river and floodplain discharge. The objective of the work presented in this paper was to investigate potential measurement errors in SWOT imagery and their hydraulic implications for a reach of the mainstem Amazon River and one of its tributaries.

## HESSD

11, 9399–9434, 2014

### Swath altimetry measurements of the mainstem Amazon River

M. D. Wilson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## 2 The Surface Water and Ocean Topography mission

Recommended for launch by the National Research Council Decadal Survey (NRC, 2007), SWOT will provide a substantial improvement in the availability of data on terrestrial surface water storage and dynamics, achieving near-global water elevation measurements in large rivers and their large floodplains. The SWOT sensor is a Ka-band radar interferometer which will allow mapping of surface water extent and elevation at a spatial resolution of around 250 m, at centimetric vertical precision when averaged over targets of interest, every 2–11 days depending on the latitude (Durand et al., 2010). Thus, SWOT will provide the first, routine two-dimensional measurements of water surface elevation, allowing the analysis of floodplain hydrodynamics and the estimation of river discharge. While SWOT will not replace a ground-based river gauge network, it will allow large ungauged rivers to be sampled and increase the level of detail and availability in river flow estimates. In addition, the two-dimensional measurements of surface water provided by SWOT will allow the detailed observation of floodplain and wetland hydrodynamics (Durand et al., 2010).

The approach used by SWOT is similar to that of LeFavour and Alsdorf (2005) and Kiel et al. (2006), who used Shuttle Radar Topography Mission (SRTM) elevation data of the water surface to obtain slopes of the Amazon and Ohio rivers and, subsequently, to estimate channel discharge. However, for the Amazon, LeFavour and Alsdorf (2005) found vertical errors 5.51 m in water surface elevations from C-band SRTM data, meaning that a long reach length of 733 km was required to reduce errors in derived water surface slopes to  $1.5 \text{ cm km}^{-1}$  for the accurate estimation of channel discharge (6.2% error at Manacapuru; 7.6% at Itapeua). For SWOT, the science requirements are for a vertical precision of 10 cm in measurements of water surface elevation and derived water surface slopes with errors of no more than  $1 \text{ cm km}^{-1}$  when averaged over a 10 km reach length (Rodríguez, 2014), substantially more accurate than measurements obtained from SRTM. For comparison, using the simple method of LeFavour and Alsdorf (2005) to determine an appropriate reach length ( $2\sigma/S_{\min}$ , where

**HESSD**

11, 9399–9434, 2014

### Swath altimetry measurements of the mainstem Amazon River

M. D. Wilson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



$\sigma$  denotes the vertical precision of the measurements and  $S_{\min}$  denotes the minimum slope required), indicates that, using the SWOT vertical precision of 10 cm, to achieve water surface slope errors of no more than  $1 \text{ cm km}^{-1}$ , reach lengths of 20 km may be required; for  $1.5 \text{ cm km}^{-1}$ , reach lengths of 13.3 km. However, this simple method may be overly conservative and does not take into account the potential for averaging over channel cross-sections. In this paper, we explore the implications of the SWOT science-requirements on the derivation of water surface slope and subsequent estimation of channel discharge.

### Virtual mission

We used a “virtual mission” study of two-dimensional observations of water surface elevation as may be obtained by SWOT, for the estimation of discharge on a  $\sim 260 \text{ km}$  reach of the central Amazon (Solimões) River at its confluence with the Purus River) and one of its tributaries (Purus) in Brazil (Fig. 1a). The Amazon is a globally significant river, carrying around 20% of total global continental runoff (Richey et al., 1989) with a monomodal flood pulse passing annually down the river. The middle reaches of the Amazon are characterized by very low water surface slopes of between 1 and  $3 \text{ cm km}^{-1}$  and significant backwater effects (Meade et al., 1991), with peak channel flow in the study site around  $120\,000 \text{ m}^3 \text{ s}^{-1}$ . This combination of low water surface slope combined with high discharge makes the estimation of discharge from SWOT challenging since surface water slope errors may have a proportionately large impact. Here, we assessed the likely accuracy which may be possible. Specifically, we aimed to (i) characterize and illustrate in two-dimensions the errors which may be found in SWOT swath altimetry measurements of terrestrial surface water, (ii) simulate the spatio-temporal sampling scheme of SWOT for the Amazon, and (iii) assess the impact of each on estimates of water surface slope and river discharge which may be obtained from SWOT imagery. Note that, presently, the performance of the SWOT instrument in the case of flooded vegetation is unknown, thus throughout this paper the

# HESSD

11, 9399–9434, 2014

## Swath altimetry measurements of the mainstem Amazon River

M. D. Wilson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



words “floodplain” and “wetland” reference those conditions of a clear view of the sky without any flooded vegetation.

We utilized the hydrodynamic model of Wilson et al. (2007) and Trigg et al. (2009) for the same reach of the Amazon. We used this model to generate water surface elevation “truth” images for a 22 month period comprising more than a full flood cycle (Fig. 1b and c). These “truth” images were then temporally sampled to match the orbital characteristics of SWOT, and 2-D errors as defined by the SWOT design requirements were added. Thus, we obtained estimates of surface water heights as may be observed by SWOT. From both the “truth” images and the simulated SWOT observations, estimates of river slope and discharge were then derived.

### 3 Methods

#### 3.1 Generation of water surface “truth” images from hydrodynamic modeling

In order to generate water elevation “truth” images, the hydrodynamic model code LISFLOOD-FP (Bates and De Roo, 2000) was used. LISFLOOD-FP consists of a 1-D representation of the river channel which comprises of a series of channel cross-sections and a 2-D floodplain representation. The formulation of LISFLOOD-FP used here was based on that of Wilson et al. (2007) and included the one-dimensional diffusive wave formulation of Trigg et al. (2009) for channel flow, allowing complex channel bathymetry and back propagation of flow in the main channel. In LISFLOOD-FP, this is implemented in the form:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \quad (1)$$

$$S_0 - \frac{n^2 P^{4/3} Q^2}{A^{10/3}} - \left[ \frac{\partial y}{\partial x} \right] = 0 \quad (2)$$

## Swath altimetry measurements of the mainstem Amazon River

M. D. Wilson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion







validation consisted of a comparison of model water levels with an independent set of satellite altimetry data, with over RMSE found to be 1.26 and 1.42 m for the Solimões and Purus rivers, respectively (Trigg et al., 2009).

### 3.2 Obtaining SWOT observations

5 Water surface elevations obtained from LISFLOOD-FP were used as “truth” onto which SWOT sampling and errors could be added, thereby allowing us to assess their hydraulic implications. Water surfaces were obtained from the model according to the SWOT spatio-temporal sampling scheme from an orbit with 78° inclination, 22 day repeat, 97 km altitude, and 140 km swath width. The reach length was sufficient to  
10 be covered by 6 swaths in total in each 22 day cycle (3 ascending, 3 descending), with each ground location being observed 2 or 3 times (Fig. 2a). Since the site is close to the equator, this represents the minimum frequency in sampling which may be obtained by SWOT. Onto the water surface images, errors were added based on a two-dimension height error spectrum derived from the SWOT design requirements (Fig. 2b). 2-D SWOT errors were generated by inverse Fourier transform of the design requirements error spectrum (Rodríguez, 2014). A separate error field at 500 m spatial resolution (resolution limited by computational power) was generated for each overpass in order to include long-wavelength errors. The 500 m SWOT errors were downscaled to model resolution (100 m), adding random noise in order to ensure that the total error variance (spectral, integral of the design requirements error spectrum) was correct.  
20

We thereby obtained water surface elevation measurements for the Amazon mainstem as may be observed by SWOT. Using these measurements, we derived estimates of river slope and discharge and compared them to those obtained directly from the hydraulic model. For completeness, we also compared discharge computed directly from the model output, i.e. the water surface slope prior to adding slope errors. This allowed us to characterize the error in water surface slope and discharge estimates from both  
25 the SWOT spatio-temporal sampling scheme and from the instrument measurement error.

## Swath altimetry measurements of the mainstem Amazon River

M. D. Wilson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



### 3.3 Calculation of slope and discharge from water surface elevations

Initially, single-pixel SWOT water surface elevation measurements ( $h_{[\text{SWOT OBS}]}$ ) were extracted along the channel centerline and used to calculate water surface slope ( $S_{[\text{SWOT OBS}]}$ ). Note that the water surface slope is mathematically equal to the sum of the bed slope ( $S_0$ ) and downstream changes in water depth [ $\partial y / \partial x$ ]:

$$S = S_0 - \frac{\partial y}{\partial x}. \quad (3)$$

$S$  was derived by along-reach averaging through the fitting of 1-D polynomials using least square estimation to moving windows placed on the surface water heights:

$$S = - \frac{\sum xh - k\bar{x}\bar{h}}{\sum x^2 - k\bar{x}^2} \quad (4)$$

where  $k$  is the number of data points included in the moving window and  $x$  is the distance of the water elevation observation,  $h$ , along the channel; the negative sign constrains the slopes to be greater than zero in the usual case when  $h$  is decreasing in the downstream direction. The size of the moving windows used ranged from 0.5 km up to 20 km, with larger windows leading to greater along-channel smoothing of the data.

This process was then repeated using cross-section averages of SWOT water elevation measurements ( $h_{[\text{SWOT XS}]}$ ), extracted by taking the arithmetic mean of pixels across-channel in a direction perpendicular to the channel centerline.  $S_{[\text{SWOT XS}]}$  was then calculated in the same way as  $S_{[\text{SWOT OBS}]}$ . For comparison and to assess accuracy of derived estimates of  $Q$ , true slope ( $S_{[\text{TRUE}]}$ ) was also calculated using water surface elevation “truth” images ( $h_{[\text{TRUE}]}$ ) using Eq. (4).

For each water surface slope ( $S_{[\text{SWOT OBS}]}$ ,  $S_{[\text{SWOT XS}]}$ ,  $S_{[\text{TRUE}]}$ ) at each reach-length, discharge along the length of the channel was derived, following the method of LeFavour and Alsdorf (2005):

$$Q = \frac{1}{n} w y^{5/3} S^{1/2} \quad (5)$$

**HESSD**

11, 9399–9434, 2014

## Swath altimetry measurements of the mainstem Amazon River

M. D. Wilson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



where  $w$  is the channel width,  $z$  is the bed elevation,  $y$  is the river depth and  $S$  is the water surface slope. In this paper, we assume that channel friction, width and bed elevation are known. Thus, the focus here is on the impact of errors in observations of water surface elevation and the derived estimates of water surface slope on the estimation of discharge. Errors in  $Q$  were approximated using first-order error propagation, via a Taylor series expansion:

$$\sigma_Q \approx \frac{\partial Q}{\partial S} \sigma_S = \frac{1}{2} Q \frac{\sigma_S}{S}. \quad (6)$$

Note that we have here isolated the uncertainty in  $Q$  that derives from  $S$ . Hydrographs of discharge over time for given points on the channel were then extracted, with the temporal frequency of these determined by the SWOT sampling scheme. Thus, for most locations on the channel, two values of  $Q$  were available in each 22 day cycle.

### 3.4 Accuracy assessment of SWOT derived discharge

In addition to the discharge error approximation ( $\sigma_Q$ ) calculated in Eq. (6), hydrographs of channel discharge obtained using along-reach averaging ( $Q_{[\text{SWOT OBS}]}$ ) and with added cross-section averaging ( $Q_{[\text{SWOT XS}]}$ ) were compared to hydrographs obtained using the “true” water surface elevation ( $Q_{[\text{TRUE}]}$ ) using a percentage error calculation and the Nash–Sutcliffe model efficiency coefficient (Nash and Sutcliffe, 1970):

$$E = 1 - \frac{\sum_{t=1}^T \left( Q_{[\text{TRUE}]}^t - Q_{[\text{PRED}]}^t \right)^2}{\sum_{t=1}^T \left( Q_{[\text{TRUE}]}^t - \overline{Q_{[\text{TRUE}]}} \right)^2} \quad (7)$$

where  $Q_{[\text{TRUE}]}^t$  is the “observed” channel discharge derived from “true” water surface elevations at time  $t$  and  $Q_{[\text{PRED}]}^t$  is channel discharge derived from SWOT observations ( $Q_{[\text{SWOT OBS}]}$  or  $Q_{[\text{SWOT XS}]}$ ). Values of  $E$  range between  $-\infty$  and 1.0, with 1.0

**Swath altimetry measurements of the mainstem Amazon River**

M. D. Wilson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



indicating a perfect match between  $Q_{[TRUE]}$  and  $Q_{[PRED]}$  and values less than zero indicating that the mean of  $Q_{[TRUE]}$  is a better predictor of true channel discharge than  $Q_{[PRED]}$  (Legates and McCabe, 1999). Generally, values of  $E$  between 0.0 and 1.0 are considered as acceptable levels of performance (Moriassi et al., 2007).

## 4 Results and discussion

### 4.1 Model output and generation of SWOT images

The LISFLOOD-FP model was run for the full 22 month period between 1 June 1995 and 31 March 1997, taking around 82 h to complete on a dual-processor compute server. The Manning's friction coefficient,  $n$ , used was 0.032 for the Solimões and 0.034 for the Purus, obtained from model calibration by Trigg et al. (2009). 1-D channel profiles outputs from the LISFLOOD-FP model are shown in Fig. 3 for low water (15 September 1995) and high water (21 June 1996), including the water surface elevation, water surface slope and channel discharge. Along channel variation in water surface slope for the Solimões ranged from 0.15 to 9.57 cm km<sup>-1</sup> at low water (mean: 1.37 cm km<sup>-1</sup>; standard deviation 1.53) and from 0.69 to 7.43 cm km<sup>-1</sup> at high water (mean: 2.19 cm km<sup>-1</sup>; standard deviation: 0.95). For the Purus, water surface slope ranged from -0.12 to 4.99 cm km<sup>-1</sup> at low water (mean: 0.50 cm km<sup>-1</sup>; standard deviation: 1.02) and from 0.17 to 3.01 cm km<sup>-1</sup> at high water (mean: 0.52 cm km<sup>-1</sup>; standard deviation: 0.35). Along channel variation in discharge was also significant: for the Solimões, this ranged from 19 765 to 32 068 m<sup>3</sup> s<sup>-1</sup> at low water (mean: 26 346 m<sup>3</sup> s<sup>-1</sup>; standard deviation: 2137.9) and from 69 918 to 116 030 m<sup>3</sup> s<sup>-1</sup> at high water (mean: 99 783 m<sup>3</sup> s<sup>-1</sup>; standard deviation 9372.3); for the Purus, discharge ranged from -2,649 to 5314 m<sup>3</sup> s<sup>-1</sup> at low water (mean: 958 m<sup>3</sup> s<sup>-1</sup>; standard deviation: 1276.4) and from 6665 to 19 276 m<sup>3</sup> s<sup>-1</sup> at high water (mean: 13 466 m<sup>3</sup> s<sup>-1</sup>; standard deviation 2958.9).

## Swath altimetry measurements of the mainstem Amazon River

M. D. Wilson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Swath altimetry measurements of the mainstem Amazon River

M. D. Wilson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Figure 4 indicates water elevation at the upstream and downstream ends of the Solimões and Purus reaches and average water surface slopes throughout the 22 month simulation period. Generally, water surface slope is lowest during the falling limb of the hydrograph and highest during the rising limb. Average water surface slope for the Solimões rose quickly to its maximum level of  $2.9 \text{ cm km}^{-1}$  during the low water period (September to November 1995), immediately after the river level at the upstream end of the channel started to rise. The maximum water surface slope in the Purus of  $1.29 \text{ cm km}^{-1}$  occurred during the low water period (October 1995), when backwater effects from the main Solimões channel were less important.

As detailed in Sect. 3.2, “truth” images of water surface elevation,  $h_{[\text{TRUE}]}$ , were generated from LISFLOOD-FP according to the SWOT spatio-temporal sampling scheme and 2-D errors were then added to the according to the 2-D SWOT science requirements height error spectrum, providing SWOT images of water surface height observations,  $h_{[\text{SWOT OBS}]}$ . An example set of six overpasses from a SWOT orbit cycle at high water (cycle 18) is shown in Fig. 5, illustrating the extent of channel which may be observed. Note that here we are focused on the main channels and have not attempted to map water elevations in the forest floodplain. A detailed inset image of the Purus/Solimões confluence for cycle 18, overpass 6 is shown in Fig. 6, illustrating the image of  $h_{[\text{SWOT OBS}]}$  alongside the corresponding image of  $h_{[\text{TRUE}]}$  and 2-D SWOT height errors.

Values of SWOT water surface height observations were extracted from images of  $h_{[\text{SWOT OBS}]}$  along the channel centerline and, in addition, averages of channel cross-sections taken perpendicular to the channel centerline were calculated ( $h_{[\text{SWOT XS}]}$ ), plotted against distance downstream for high water (cycle 18) in Fig. 7. In these profiles, the tighter clustering of the cross-section averages to the true channel water elevation profile indicates clearly that by taking a cross-section average, errors in water surface height observations were reduced.

## 4.2 Water surface slopes

Figure 8 illustrates along-channel water surface slope as calculated using  $h_{[SWOT\ XS]}$  for high water (cycle 18, overpass 6), using reach-lengths between 5 and 20 km. As the length of averaging increased, errors in  $S_{[SWOT\ XS]}$  reduced substantially when compared to  $S_{[TRUE]}$ . Overall error in the estimation of water surface slope decreased quickly with increasing reach-lengths (Fig. 9): for the Solimões, without averaging across channel ( $S_{[SWOT\ OBS]}$ ) and with a short reach lengths of 0.5 km, errors in slope were high at  $86.4\text{ cm km}^{-1}$ . These errors dropped quickly as more data were included in the estimation of slope, reducing to  $0.33\text{ cm km}^{-1}$  at 20 km. Averaging across channel in addition to along reach lengths ( $S_{[SWOT\ XS]}$ ) led to a further drop in errors, with  $23.2\text{ cm km}^{-1}$  error at a reach length of 0.5 km, reducing to  $0.09\text{ cm km}^{-1}$  at 20 km. Slope errors were similar for the Purus without cross-section averaging ( $91.0\text{ cm km}^{-1}$  at 0.5 km;  $0.31$  at 20 km), and were moderately higher than the Solimões with cross-section averaging ( $36.0$  at 0.5;  $0.13$  at 20) due to the narrower channel width. The science-requirement for the SWOT sensor is that river slopes are measured with errors less than  $1\text{ cm km}^{-1}$  when averaged for 10 km reach length (Rodríguez, 2014). For both the Solimões and Purus, without cross-section averaging ( $S_{[SWOT\ OBS]}$ ), reach-lengths of  $\sim 10\text{ km}$  were required to achieve this level of accuracy; with cross-section averaging ( $S_{[SWOT\ XS]}$ ) accuracies better than  $1\text{ cm km}^{-1}$  were achieved using shorter reach lengths of  $\sim 4\text{ km}$  and  $\sim 5\text{ km}$  for the Solimões and Purus, respectively. For 10 km reach lengths, incorporating cross-section averaging, water slope errors of 0.26 and 0.37 cm per km, respectively, were achieved.

## 4.3 Channel discharge

In Fig. 10, along-channel discharge estimates for high water (cycle 18, overpass 6) are shown for  $Q_{[SWOT\ XS]}$  using reach lengths between 5 and 20 km. As with errors in slope, as reach lengths increased, the errors in estimated discharge decreased. The

# HESSD

11, 9399–9434, 2014

## Swath altimetry measurements of the mainstem Amazon River

M. D. Wilson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion









## 4.4 Implications for SWOT

These results indicate that discharge may be obtained accurately from SWOT measurements on large, lowland rivers, assuming sufficient knowledge of channel bathymetry and frictional properties. The error in discharge of 2.6% for the Solimões using cross-channel averaging and 20 km reach lengths compares favorably with the error of ~6–8% obtained by LeFavour and Alsdorf (2005) for the same section of river using SRTM data and 733 km reach lengths. When comparing against instantaneous discharge obtained directly from model output, errors were moderately higher with accuracies of 9.1% obtained at reach lengths of 12.5 km. This suggests that SWOT data will provide both an improvement in accuracy of discharge estimates and a substantial increase in the level of along-channel detail. Since SWOT will provide 2-D measurements of surface water, we were able to use cross-channel averaging to substantially improve accuracy due to the improved representation of channel water surface elevations and subsequent reductions in water surface slope errors. For the Purus, accuracy in discharge estimates was lower, which is likely to have been in large part due to the narrower width of the river leading to a reduction in averaging of height errors and consequently higher slope errors, combined with the very low water surface slopes on the river leading to a proportionately higher impact of slope errors when calculating discharge. From this, we can infer that discharge estimates may be more accurate for rivers with: (i) greater channel widths which permit a greater level of cross-section averaging and the use of shorter reach lengths; and (ii) higher water surface slopes, since, from Eq. (6), the relative error in discharge decreases as slope increases. Conversely, discharge estimation accuracy is likely to be lowest for narrow rivers with low slopes, although further research is required to quantify errors for rivers at this scale.

Note that the error analysis presented here excluded layover and vegetation effects, as may be found in wetlands and floodplains, or along the edges of rivers. These effects are likely to be greatest for narrower rivers with bank vegetation. In addition, research presented here did not incorporate effects of the temporal sampling scheme on the

HESSD

11, 9399–9434, 2014

### Swath altimetry measurements of the mainstem Amazon River

M. D. Wilson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



accuracy of hydrograph estimation. For large rivers with discharge which changes relatively slowly, such as the Amazon and its sub-basins, errors introduced by SWOT temporal sampling are likely to be minimal. However, for smaller rivers with higher discharge variability, this sampling may be significant. Further research is required in this area, although it is likely that there will be an optimum level of width, slope and discharge variability for discharge estimation.

## 5 Conclusions

In this paper, we used a “virtual mission” study of two-dimensional water surface elevations which may be obtained by SWOT for a reach of the central Amazon River in Brazil and investigated the implications of errors in such measurements on the estimation of water surface slope and channel discharge. The following remarks can be made following our work:

1. Using 1-D polynomials with least squares estimation fitted to water elevations obtained from channel centerlines, the SWOT design requirement of slope errors less than  $1 \text{ cm km}^{-1}$  when averaged for 10 km (Rodríguez, 2014) was achieved for both the Solimões and Purus Rivers.
2. Shorter reach lengths ( $\sim 4$  and  $\sim 5$  km for the Solimões and Purus, respectively) were required to achieve the design level of accuracy when additionally averaging SWOT water surface height estimates across-channel; for 10 km reach lengths, higher accuracies were achieved (water slope errors of  $0.26$  and  $0.37 \text{ cm km}^{-1}$  for the Solimões and Purus, respectively). This indicates that the accuracy of water surface slopes estimates will be higher for rivers with wider channels, particularly those several times wider than the  $\sim 250$  m nominal spatial resolution (Durand et al., 2010).
3. SWOT data are promising for the estimation of Amazonian river discharge, with low errors in estimates (9.1% for instantaneous estimates, or 2.6%

## Swath altimetry measurements of the mainstem Amazon River

M. D. Wilson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion







**HESSD**

11, 9399–9434, 2014

**Swath altimetry  
measurements of the  
mainstem Amazon  
River**

M. D. Wilson et al.

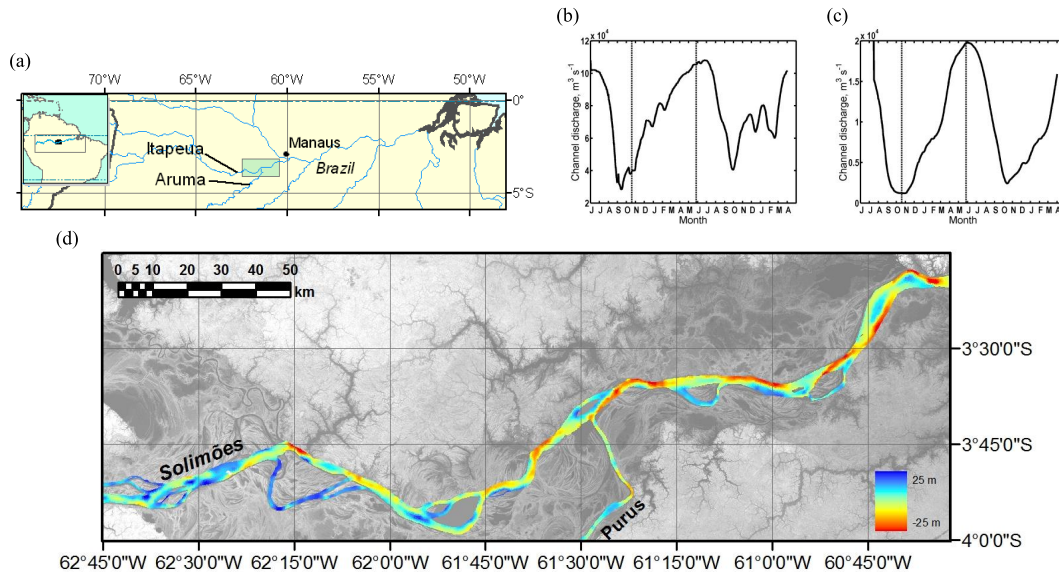
[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

- Lambin, J., Morrow, R., Fu, L.-L., Willis, J. K., Bonekamp, H., Lillibridge, J., Perbos, J., Zaouche, G., Vaze, P., Bannoura, W., Parisot, F., Thouvenot, E., Coutin-Faye, S., Lindstrom, E., and Mignogno, M.: The OSTM/Jason-2 Mission, *Mar. Geod.*, 33, 4–25, doi:10.1080/01490419.2010.491030, 2010. 9402
- 5 LeFavour, G. and Alsdorf, D.: Water slope and discharge in the Amazon River estimated using the shuttle radar topography mission digital elevation model, *Geophys. Res. Lett.*, 32, 1–5, doi:10.1029/2005GL023836, 2005. 9404, 9409, 9416
- Legates, D. R. and McCabe, G. J.: Evaluating the use of “goodness-of-fit” measures in hydrologic and hydroclimatic model validation, *Water Resour. Res.*, 35, 233–241, doi:10.1029/1998WR900018, 1999. 9411
- 10 Meade, R. H., Rayol, J. M., Conceição, S. C., and Natividade, J. R. G.: Backwater effects in the Amazon River basin of Brazil, *Environ. Geol. Water S.*, 18, 105–114, doi:10.1007/BF01704664, 1991. 9405
- Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., and Veith, T. L.: Model evaluation guidelines for systematic quantification of accuracy in watershed simulations, *T. ASABE*, 50, 885–900, doi:10.13031/2013.23153, 2007. 9411
- 15 Nash, J. and Sutcliffe, J.: River flow forecasting through conceptual models part I – a discussion of principles, *J. Hydrol.*, 10, 282–290, doi:10.1016/0022-1694(70)90255-6, 1970. 9410
- NRC: Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond, National Academies Press, Washington, D.C., [http://www.nap.edu/catalog.php?record\\_id=11820](http://www.nap.edu/catalog.php?record_id=11820) (last access: 1 August 2014), 2007. 9404
- 20 NSTC: Science and technology to support fresh water availability in the United States, Tech. Rep. November, National Science and Technology Council, Committee on Environment and Natural Resources, subcommittee on Water Availability and Quality, Washington, D.C., <http://water.usgs.gov/owq/swaq.pdf> (last access: 1 August 2014), 2004. 9401
- 25 Papa, F., Bala, S. K., Pandey, R. K., Durand, F., Gopalakrishna, V. V., Rahman, A., and Rossow, W. B.: Ganga-Brahmaputra river discharge from Jason-2 radar altimetry: an update to the long-term satellite-derived estimates of continental freshwater forcing flux into the Bay of Bengal, *J. Geophys. Res.*, 117, C11021, doi:10.1029/2012JC008158, 2012. 9402
- 30 Richey, J. E., Nobre, C., and Deser, C.: Amazon river discharge and climate variability: 1903 to 1985, *Science*, 246, 101–103, doi:10.1126/science.246.4926.101, 1989. 9405



## Swath altimetry measurements of the mainstem Amazon River

M. D. Wilson et al.



**Figure 1.** Study area: (a) location of site in the central Amazon, Brazil; (b) Solimões and (c) Purus inflow hydrographs; and (d) SRTM elevation fused with river bathymetry used in hydraulic model.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

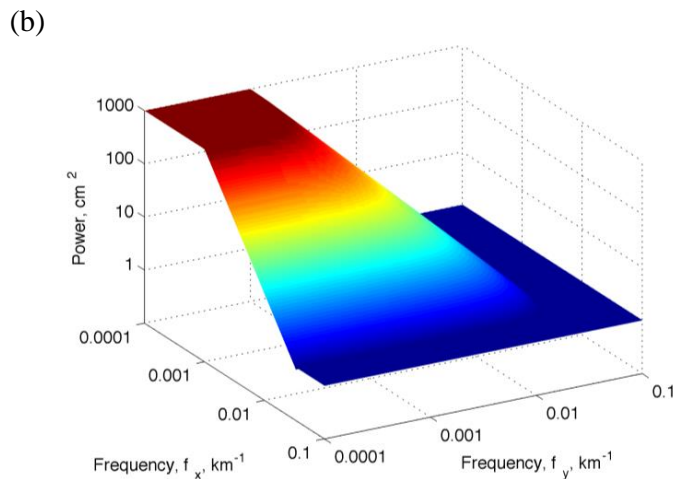
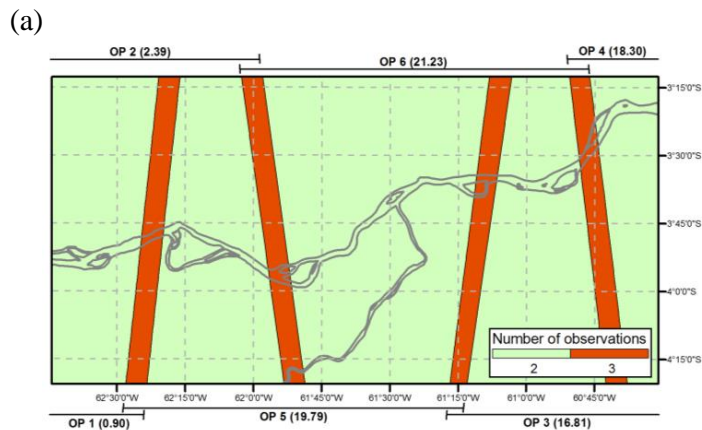
Interactive Discussion





## Swath altimetry measurements of the mainstem Amazon River

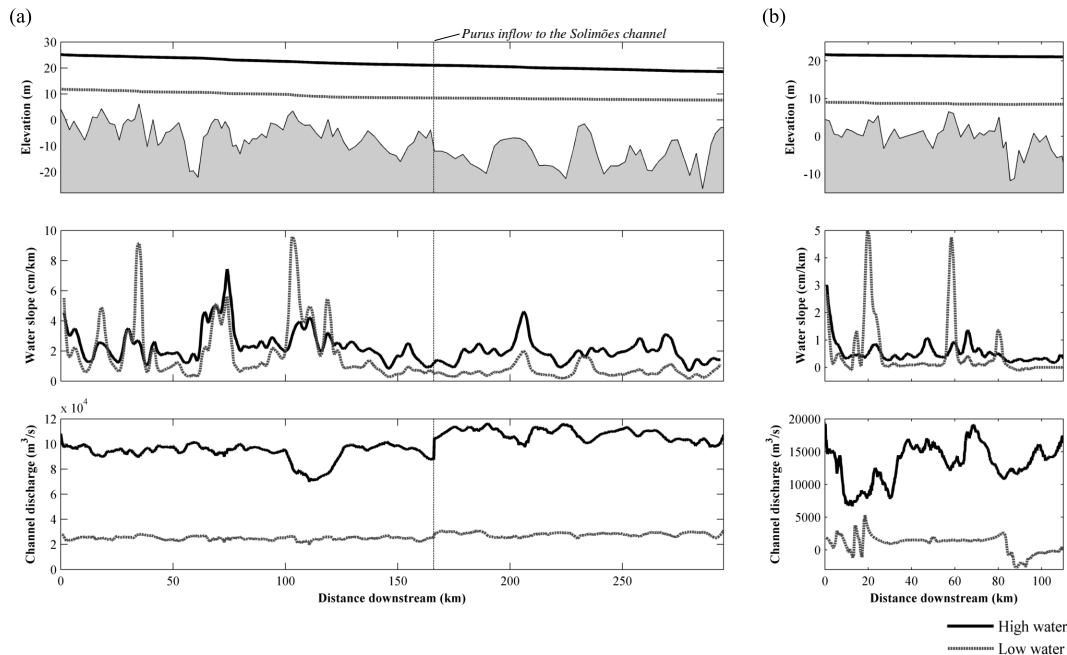
M. D. Wilson et al.



**Figure 2.** (a) Spatio-temporal sampling for a given cycle, including overpass timings (days from cycle start) during each 22 day cycle; (b) 2-D SWOT science requirements height error spectrum.

## Swath altimetry measurements of the mainstem Amazon River

M. D. Wilson et al.

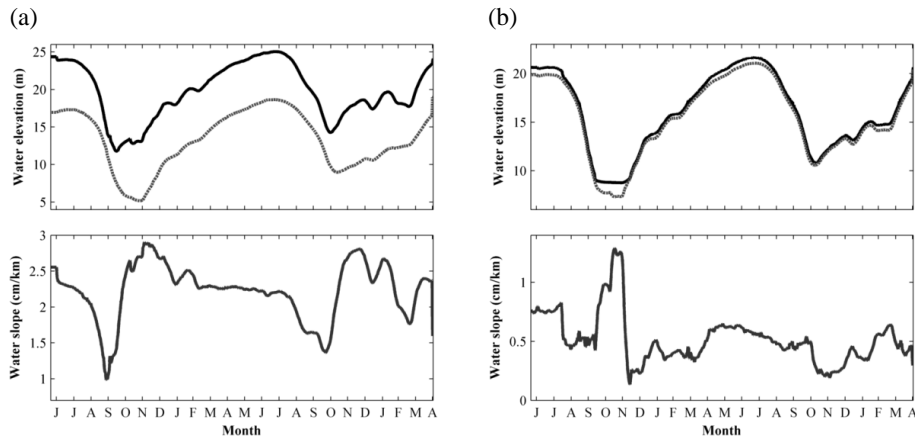


**Figure 3.** LISFLOOD-FP model output: 1-D channel profiles at high and low water for **(a)** the Solimões and **(b)** Purus rivers. Top: water surface elevations along the channel (channel bed topography is shown in gray shaded area); middle: water surface slope; bottom: channel discharge. The vertical line in the plots in **(a)** indicates the location of the Purus inflow to the Solimões.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[⏪](#)
[⏩](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

## Swath altimetry measurements of the mainstem Amazon River

M. D. Wilson et al.



**Figure 4.** LISFLOOD-FP model output: 1-D channel profiles through time for **(a)** the Solimões and **(b)** the Purus rivers. Top panels: water elevations at the upstream (solid line) and downstream (dotted line) end of the study reach; bottom panels: average water surface slope through time.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

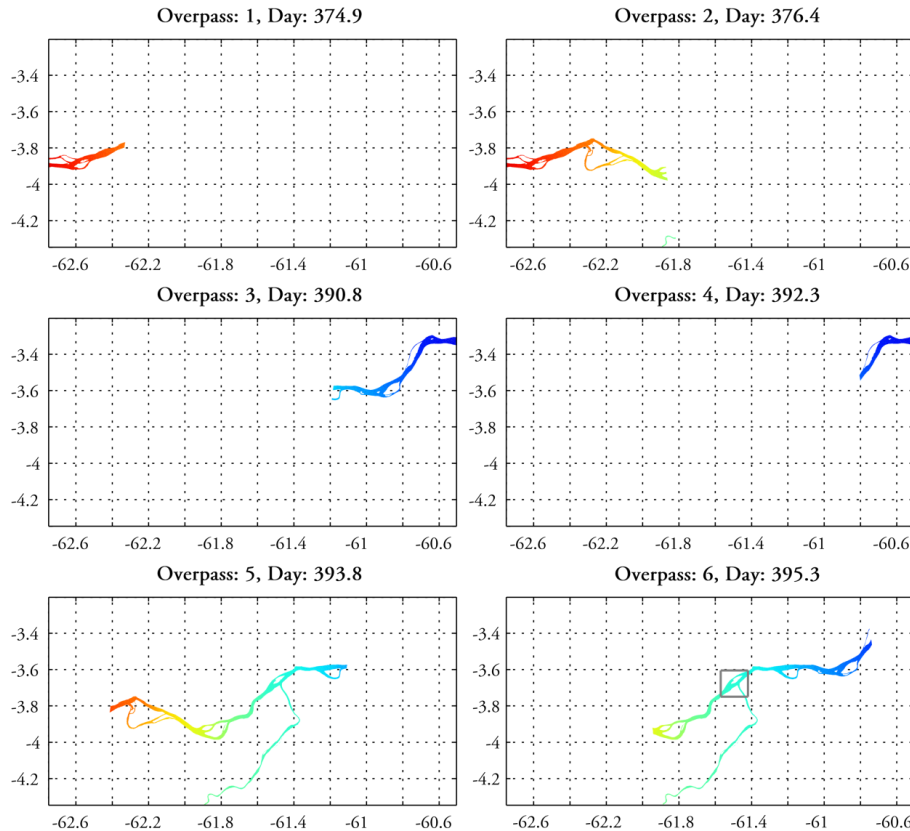
Printer-friendly Version

Interactive Discussion



## Swath altimetry measurements of the mainstem Amazon River

M. D. Wilson et al.



**Figure 5.** SWOT water elevation measurements derived from hydraulic model output (Figs. 3 and 4) and science requirements (Fig. 2) for cycle 18 (high water), overpasses 1 to 6. The box shown in overpass 6 indicates the area shown in detail in Fig. 6.

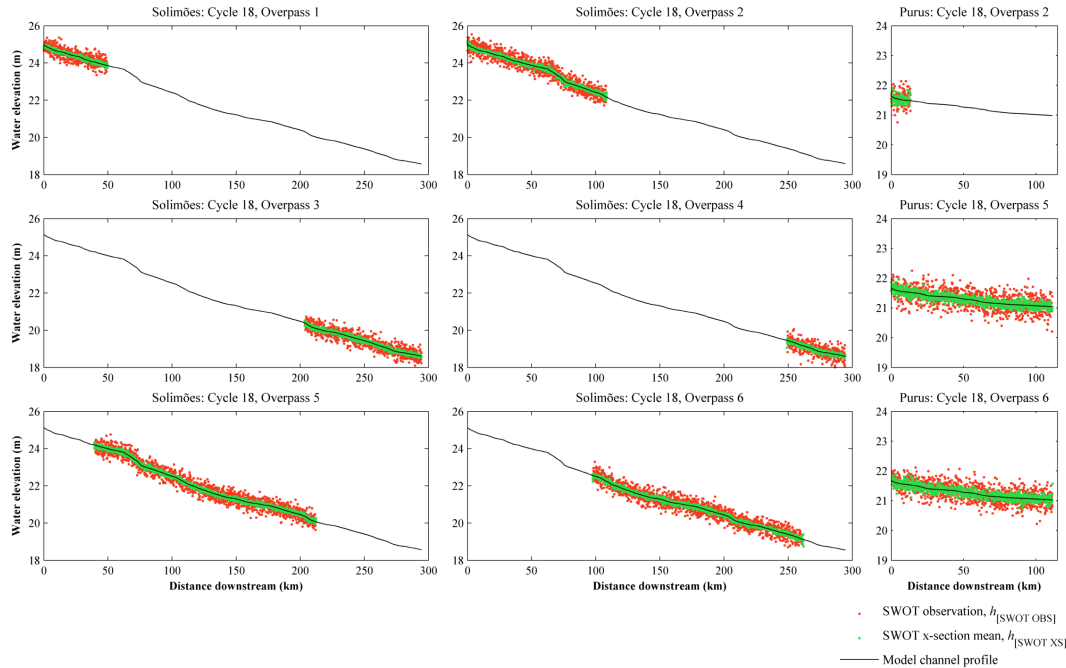
[Title Page](#)  
[Abstract](#)   [Introduction](#)  
[Conclusions](#)   [References](#)  
[Tables](#)   [Figures](#)  
[⏪](#)   [⏩](#)  
[◀](#)   [▶](#)  
[Back](#)   [Close](#)  
[Full Screen / Esc](#)  
[Printer-friendly Version](#)  
[Interactive Discussion](#)





## Swath altimetry measurements of the mainstem Amazon River

M. D. Wilson et al.



**Figure 7.** The 2-D heights (Fig. 5) were transferred to 1-D for both the Solimões and Purus by extracting values of  $h_{[SWOT\ OBS]}$  along the channel centerline; to reduce errors, averages of cross-sections taken perpendicular to the channel centerline were also calculated ( $h_{[SWOT\ XS]}$ ).

[Title Page](#)

[Abstract](#)   [Introduction](#)

[Conclusions](#)   [References](#)

[Tables](#)   [Figures](#)

[◀](#)   [▶](#)

[◀](#)   [▶](#)

[Back](#)   [Close](#)

[Full Screen / Esc](#)

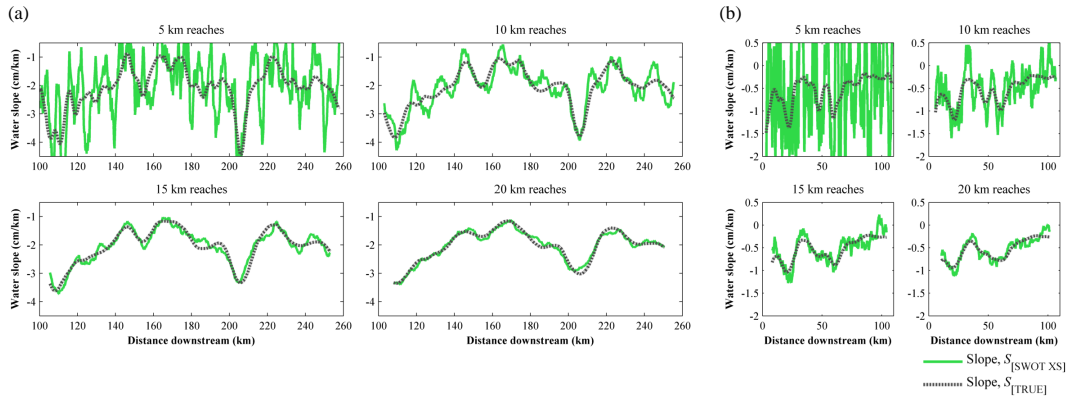
[Printer-friendly Version](#)

[Interactive Discussion](#)



## Swath altimetry measurements of the mainstem Amazon River

M. D. Wilson et al.



**Figure 8.** Slope errors: the effect of averaging along channel using reach lengths between 5 and 20 km for the (a) Solimões and (b) Purus rivers. Plots show cycle 18 (high water), overpass 6.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

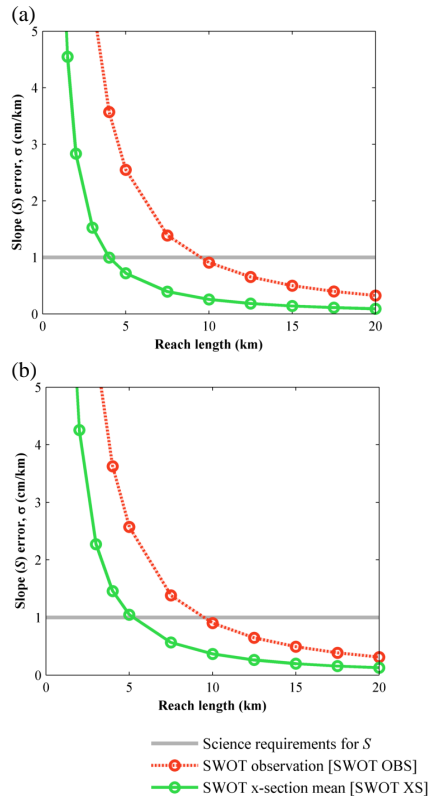
Printer-friendly Version

Interactive Discussion



## Swath altimetry measurements of the mainstem Amazon River

M. D. Wilson et al.



**Figure 9.** The effect of reach-length averaging on errors in the water surface slope estimation for (a) the Solimões and (b) the Purus rivers.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

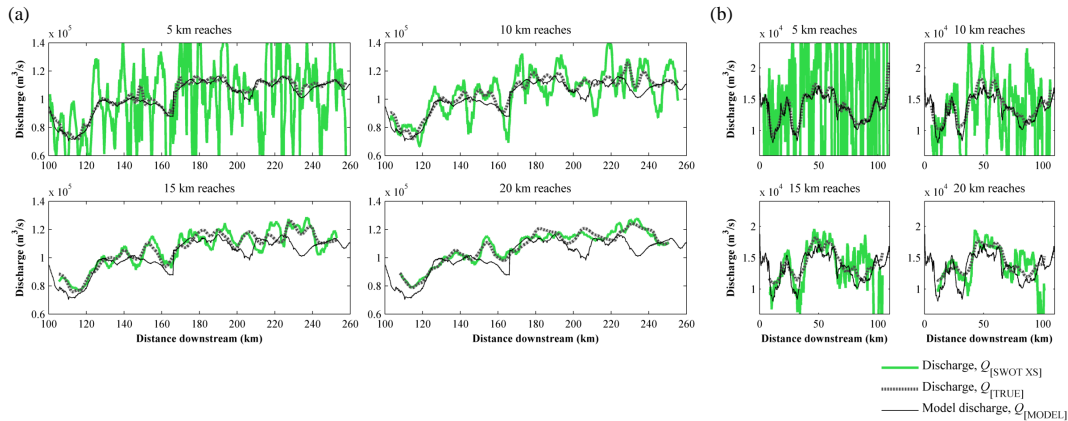
Interactive Discussion





## Swath altimetry measurements of the mainstem Amazon River

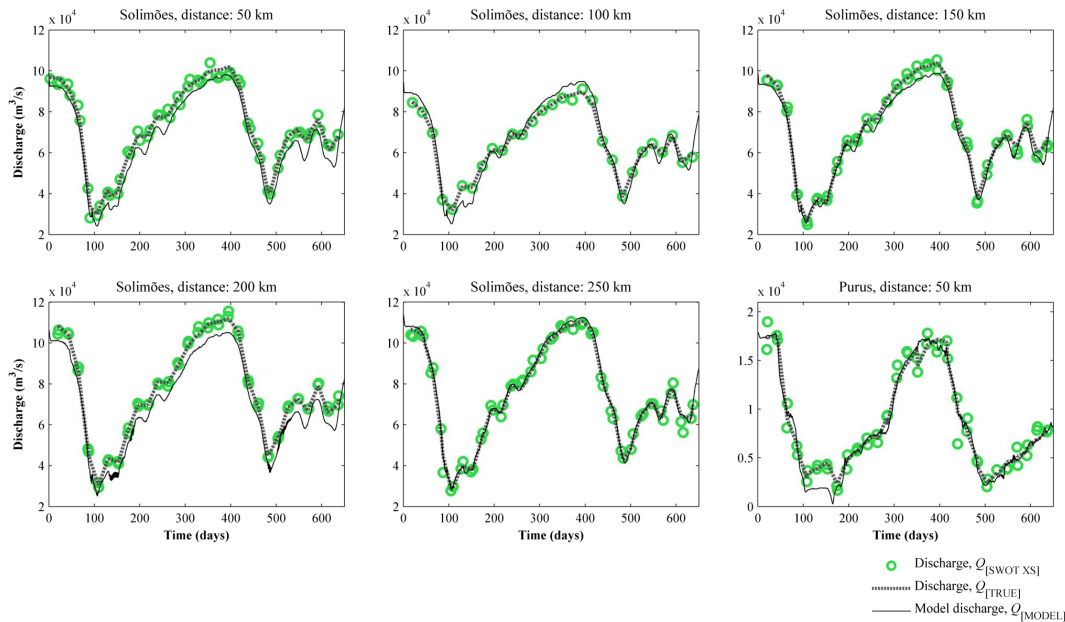
M. D. Wilson et al.



**Figure 10.** Discharge estimates accounting for slope errors but neglecting width, depth, and friction errors for reach lengths between 5 and 20 km for the (a) Solimões and (b) Purus rivers. Plots show cycle 18 (high water), overpass 6.

## Swath altimetry measurements of the mainstem Amazon River

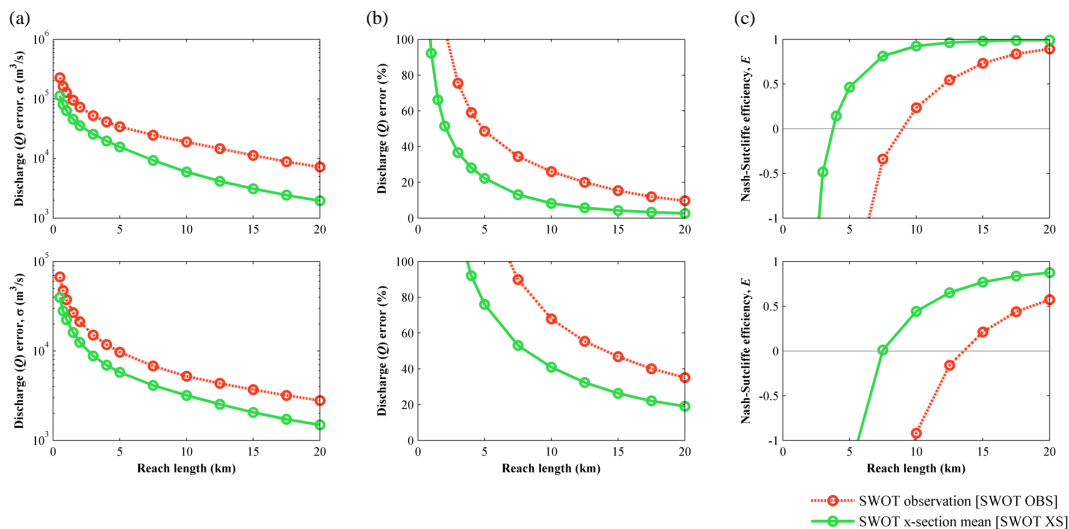
M. D. Wilson et al.



**Figure 11.** Reconstruction of channel discharge hydrographs from cross-section averaged SWOT observations ( $Q_{[SWOT\ XS]}$ ) for the Solimões and Purus channels using 20 km reach lengths, compared to discharge obtained using water elevation “truth” images ( $Q_{[TRUE]}$ ) and the original modeled channel discharge ( $Q_{[MODEL]}$ ).

## Swath altimetry measurements of the mainstem Amazon River

M. D. Wilson et al.

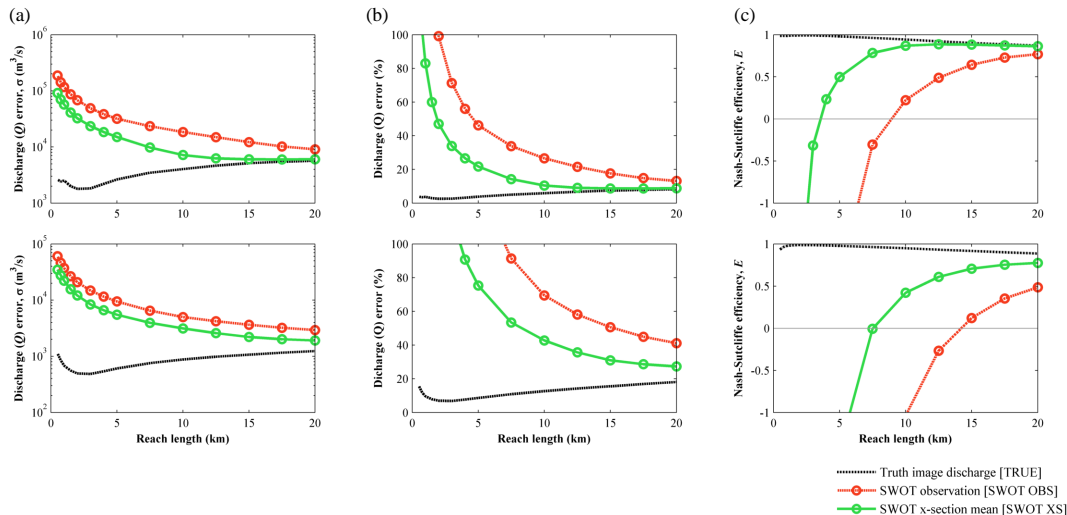


**Figure 12.** Errors in discharge ( $Q$ ) as related to reach-length averaging, calculated against slope and discharge obtained using water elevation “truth” images ( $Q_{\text{TRUE}}$ ): **(a)** absolute discharge error; **(b)** error expressed as a percentage of mean discharge; and **(c)** Nash–Sutcliffe efficiency coefficient. The horizontal line in **(c)** represents the level of “acceptable” error in modeled discharge estimates. Top row: Solimões; bottom row: Purus.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

## Swath altimetry measurements of the mainstem Amazon River

M. D. Wilson et al.



**Figure 13.** Errors in discharge ( $Q$ ) calculated against model discharge ( $Q_{[MODEL]}$ ): **(a)** absolute discharge error; **(b)** error expressed as a percentage of mean discharge; and **(c)** Nash–Sutcliffe efficiency coefficient. Top row: Solimões; bottom row: Purus.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[⏪](#)
[⏩](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)
