RECENT PROGRESS IN DEVELOPMENT OF SWOT RIVER DISCHARGE ALGORITHMS

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ABSTRACT

The Surface Water and Ocean Topography (SWOT) Mission is a satellite mission under joint development by NASA and CNES. The mission will use interferometric synthetic aperture radar technology to continuously map, for the first time, water surface elevations and water surface extents in rivers, lakes, and oceans at high spatial resolutions. Among the primary goals of SWOT is the accurate retrieval of river discharge directly from SWOT measurements. Although central to SWOT, discharge retrieval represents a unique challenge due to uncertainties in SWOT measurements and because traditional discharge algorithms are not optimized for SWOT-like measurements. However, recent work suggests that SWOT may also have unique strengths that can be exploited to yield accurate estimates of discharge. A NASA-sponsored workshop convened June 18-20, 2012 at the University of North Carolina focused on progress and challenges in developing SWOT-specific discharge algorithms. Workshop participants agreed that the most viable approach to discharge estimation will be based on a slope-area scaling method such as Manning's equation, but modified slightly to reflect the fact that SWOT will estimate reach-averaged rather than cross-sectional discharge. While SWOT will provide direct measurements of some key parameters such as width and slope, others such as baseflow depth and channel roughness must be estimated. Fortunately, recent progress has suggested several algorithms that may allow the simultaneous estimation of these quantities from SWOT observations by using multitemporal observations over several adjacent reaches. However, these algorithms require validation, which will necessitate the collection of new field measurements, airborne imagery from AirSWOT (a SWOT analogue), and compilation of global datasets of channel roughness, river width, and other relevant variables.

1. INTRODUCTION

Flow of water through rivers is a critical component of the global hydrologic cycle, and water in rivers represents both a major hazard and a substantial resource for human societies and natural ecosystems. Currently, river discharge is estimated using labor-intensive empirical stage-discharge relationships combined with continuous *in situ* water surface elevations. As a result, present-day discharge on many rivers remains poorly observed via *in situ* gauge networks. In some countries data are simply not collected, while in others discharge data are not released to the public because of national security concerns [1]. Indeed, in remote regions such as the Arctic and much of Africa discharge gauge networks have declined markedly in recent decades [2]. Even where ground-based discharge measurements are plentiful they are of limited utility for some applications (e.g. flood modelling) because they are not collected continuously along river channels.

In response to the limitations of existing *in situ* measurements, research has recently focused on developing new ways to estimate river discharge from satellite imagery [3,4,5]. Most of these efforts have developed empirical relationships between *in situ* discharge and either inundation extent or water surface elevation, and they are thus inherently limited to areas with existing gauge networks. In contrast, the planned NASA/CNES Surface Water and Ocean Topography (SWOT) satellite mission will provide concurrent observations of water surface elevation, its spatial derivative (surface slope), and inundated area for rivers wider than 50-100 m, which will allow a step-change improvement in characterization of river discharge from space. However, because SWOT observations will be both spatially continuous and limited to measuring properties observable at the surface (i.e. water surface extent and elevation), new discharge algorithms will be needed to produce SWOT-based discharge estimates.

Leading researchers in remote sensing of river discharge recently met in Chapel Hill, NC at a NASA-funded workshop to discuss new approaches for incorporation of SWOT's unprecedented observations into discharge estimation algorithms. Workshop participants discussed the current state of SWOT discharge algorithms, identified major sources of error and algorithmic uncertainty, and recommended future courses of research. These findings are summarized below.

2. THE CURRENT STATE OF SWOT DISCHARGE ALGORITHMS

While discharge is usually measured or estimated at ground-based river cross-sections, SWOT will estimate discharge over river reaches of variable length. As such, current equations for measuring discharge will require modification in order to accept SWOT observations. Workshop participants unanimously agreed that a slope-area scaling method such as Manning's Equation:

$$Q = \frac{AR^{2/3}S^{1/2}}{n} \qquad (1)$$

in which Q is discharge, A is cross-sectional area, R is hydraulic radius, S is water surface slope, and n represents channel roughness, is the most viable method for estimating discharge from SWOT, under the assumption that empirical relationships based on ground-based discharge observations are not a viable choice. However, when using reach-averaged quantities as inputs, Eq. 1 no longer applies unless a correction factor κ is applied to account for reach averaging [6], as in:

$$Q = \frac{\overline{A}\,\overline{R}^{2/3}\,\overline{S}^{1/2}}{n(1+\kappa)} \qquad (2)$$

where cross-sectional area, hydraulic radius, and slope are now reach-averaged quantities. This modified version of Manning's equation provides the framework for the most promising SWOT-based discharge algorithms.

SWOT will directly measure some of the quantities required by slope-area scaling methods, including river width and along-channel slope. Other components of equation (2), including baseflow depth and channel roughness, however, will not be directly measured. Findings from the workshop on the prospects of estimating each of these from SWOT observations and ancillary data are summarized in section 3.1.

In cases where it may be difficult to directly observe discharge-relevant quantities from SWOT, recent advances suggest that it may be possible to estimate both channel roughness and baseflow depth simultaneously from SWOT observations alone if given multiple overpasses over several adjacent river reaches [7,8]. With the acquisition of these two unknowns, discharge can be estimated directly from SWOT. This pioneering method starts from equations of mass and momentum conservation, applies the reach-averaged Manning's Equation (Eq. 2), assumes the roughness coefficient and bathymetry are temporally-invariant, then solves for the unknowns by constraining over a number of overpasses. In principle, only four overpasses are needed to determine discharge, but in practice more will likely be needed for an accurate solution; workshop participants agreed that determining the actual number required is an immediate research priority. While recent work suggests that this algorithm functions on its own, best results are achieved with information on baseflow depth at one or more locations along a river reach [8]. Discussion of a technique for estimating baseflow depth from SWOT data is included in Section 3.1.

3. SOURCES OF ERROR IN SWOT DISCHARGE ESTIMATES

In addition to uncertainty in the mathematical form of the best SWOT discharge algorithm(s), there is also substantial uncertainty regarding the sources and magnitude of error in SWOT discharge estimates. Likely sources of error can be divided into two categories: (1) errors associated with the algorithm(s) chosen to estimate discharge and (2) errors inherent in SWOT measurements of inundation extent, water surface elevation, and slope that will also impact discharge estimates.

3.1 Algorithmic Errors

The principle sources of algorithmic error relate to the necessity of estimating baseflow depth and channel roughness (Manning's n). SWOT will directly measure water surface elevation at every overpass and thus will provide information on all changes in river depth above the level of the lowest-water elevation overpass. Because absolute river depth is required to calculate discharge, however, this baseflow depth must be estimated. Perhaps the most promising methods of estimating baseflow depth alone is to simply extrapolate relationships between width and stage formed over multiple SWOT overpasses [9]. In many test locations, this method produces depth errors of less than 20%. However, there are also many places where it cannot produce accurate estimates. For example, in rivers with near-vertical banks there is little relationship between width and depth. Fortunately, if depth is constrained in a sufficient number of locations by this method it can then be extrapolated to other locations by using multitemporal SWOT observations as discussed in Section 2. A research priority in the near future is the determination of how well extrapolation of width-depth relationships functions in a wide variety of river morphologies. This work will require the development of new detailed datasets of river bathymetry using ground-based survey methods.

In contrast to baseflow depth, there is no obvious way to measure channel roughness (Manning's n) directly from SWOT observations alone. Although often treated as constant, roughness depends on a wide range of physical parameters, including the sediment grain size of the bed and banks, channel sinuosity, density and type of in-stream vegetation, and channel slope [10,11]. Some of these (e.g. sinuosity and slope) can be measured directly from SWOT, but other factors (e.g. sediment grain size) must be parameterized. There are several significant obstacles to estimating channel roughness over wide regions. First, although it is common to assume that roughness is time-invariant, this is in fact not the case. In general, roughness decreases with increasing flow until overbank flooding occurs [10]. Second, there is no large existing database of channel roughness values against which to validate estimates. Values are usually determined empirically for individual studies, and the ordinary method of calculating channel roughness requires knowledge of all other factors for measuring discharge. As such, the possibility of estimating channel roughness from multiple SWOT overpasses over multiple timesteps as described in Section 2 [7,8] is likely the best option currently known despite the required assumption of time-invariant channel roughness. Recent studies have shown the utility of repeat pass SWOT-like SAR measurements in improving the accuracy of channel and floodplain roughness estimate [12]. Nonetheless, more information on the global distribution of roughness values is essential for validation purposes.

3.2 Measurement Errors

Errors in SWOT measurements of inundated area and river width will play a significant role in determining the accuracy of SWOT discharge estimates. There are many factors likely to affect inundation retrievals, though the pertinent factors will vary depending on location. Compared to wide, single-channel rivers, errors in inundation extent will play a larger role in determining discharge accuracy in narrow rivers and rivers with multiple channels. Layover effects associated with radar returns from topography and vegetation near the river channel will hamper accurate inundation retrievals in some areas. Because no radar instrument operating in Ka band with SWOT's viewing geometry has yet been flown, there is limited understanding of the relevant radar phenomenology. As such, the amount of smoothing needed to remove speckle and the impact of factors such as water-saturated sediment and vegetation on correct classification of inundation remain uncertain. This is especially true in floodplain environments, where dense vegetation canopies may obscure observation of inundation in some cases. Observation of riverine environments with ground-based and aircraft-mounted SWOT analogues will help characterize SWOT phenomenology at selected test sites.

Accurate characterization of errors in SWOT-derived inundation extent globally will first require an understanding of which rivers SWOT will observe. The relevant mission science requirement is for observation of rivers wider than 100m, with a goal of rivers 50m wide. Efforts are currently underway to estimate the extent of these rivers, first through hydraulic geometry relationships [13,14] and later through maps derived from existing satellite imagery [15]. These global river width datasets can then be merged with information on vegetation, topography, and other factors to better understand likely patterns of error in SWOT inundation extent.

Compared to errors in inundation extent, errors in SWOT water surface elevation and slope retrievals are somewhat better characterized [16]. Most uncertainty is associated with instrumental error and the influence of the atmosphere on signal propagation, and in combination these factors are likely to produce total errors <10 cm when averaged over a 1 km^2 region. Because some of the errors associated with atmospheric effects have long spatial correlation lengths, in many cases errors in slope will be dramatically lower than for elevation alone, on the order of 1 cm/km over a 10 km reach. Although these sources of error are relatively well understood, analysis of SWOT-like data prior to launch remains essential in order to demonstrate that height retrievals meet expected levels of accuracy.

4. OPEN QUESTIONS ON SWOT DISCHARGE

One of the principal purposes of the SWOT Discharge Algorithms Workshop was to identify key unanswered questions related to SWOT discharge that could guide future work. Workshop participants identified eight key questions:

- *How should the channel roughness parameter be estimated?* One possibility, described in Sections 2 and 3, is to determine directly through multitemporal SWOT observations across several adjacent reaches. However, even in this case the availability of a global or near-global dataset of accurate roughness parameters is essential to validate output. Developing such a dataset is quite important, since no consistent estimate of channel roughness is currently available, especially for large rivers. This dataset will also improve understanding of the scales of spatial and temporal variability in roughness, neither of which is currently well understood.

- *For algorithms using multiple SWOT overpasses to estimate discharge or baseflow depth, how many overpasses are required?* At present, the most promising methods for discharge and baseflow depth estimation require at least four, and possibly many more, overpasses at different discharges to be successful. An improved understanding of how many observations are required is essential in determining whether these algorithms are, indeed, the best choices for SWOT discharge estimation.

- *What are SWOT's water-detection capabilities in floodplains and in vegetated areas?* It is unclear exactly how well SWOT will observe water under dense vegetation (e.g. on forested floodplains). The ability to do so is quite important for estimation of wet-season discharge on many tropical rivers as well as accurate characterization of flood conditions on mid-latitude rivers. It is critical that, prior to launch, SWOT's ability to observe inundation boundaries and water surface slopes in vegetated areas be well understood.

- *What is the role of data assimilation methods in estimating instantaneous discharge?* In parallel with efforts to estimate instantaneous discharge from SWOT data alone, extensive work has focused on assimilating synthetic SWOT observations into hydrodynamic models to provide continuous discharge estimates. However, it may be possible to improve instantaneous discharge estimates using data assimilation as well.

- *How can non-SWOT datasets be used to improve discharge algorithms and reduce error?* Although the workshop focused on estimating discharge from SWOT alone, it is clear that currently or potentially available datasets from other sources could help improve SWOT discharge estimates either directly or by acting as a source of validation. For example, information on channel roughness from other sources may be important to SWOT discharge estimates.

- *What are the levels of error associated with discharge algorithms, other than observational error?* Estimation of channel roughness and baseflow depth will increase the uncertainty in SWOT discharge. However, the amount of error associated with these estimates must be constrained by applying the estimation methods to a range of different river morphologies and discharges.

- *How will discharge algorithms handle lateral inflows and outflows within reaches?* In many rivers worldwide, a substantial fraction of discharge is extracted for irrigation purposes. All rivers also have tributaries that will be too small to be imaged by SWOT. It remains unclear how best to handle these from an algorithm perspective—is it best to parameterize them using non-SWOT datasets, or should they be handled in some other way?

- *How does the overall discharge error budget vary in time and space?* In what areas do measurement errors dominate? What about algorithm errors? Answering these questions will ultimately require answering many of the other questions presented here. The answers will help guide algorithm refinement and will help us understand how SWOT capabilities match observational needs for river discharge on the global scale.

5. RECOMMENDATIONS FOR FUTURE RESEARCH TOOLS AND EXPERIMENTS

5.1 Research Tools

In order to properly address the questions identified in Section 4, new validation experiments are an essential requirement. Many of these experiments will also have value beyond the SWOT mission itself by improving understanding of global patterns in hydrology. In order to perform these experiments, two new tools are required. The first is AirSWOT an airborne analogue for SWOT currently in the final stages of development [17]. AirSWOT will provide repeated SWOT-like observations over selected validation sites to improve understanding of SWOT phenomenology and allow testing of discharge algorithms. AirSWOT will also feature a high-resolution visible and near-infrared camera at wavelengths analogous to Landsat ETM+ for validation of water surface extent, vegetation type, and other relevant variables.

The second tool, yet to be developed but informally called BoatSWOT, is a boat-based platform that can simultaneously collect all of the necessary data to validate SWOT discharge algorithms. Necessary observations include the following:

- Merged above-water topography and bathymetry acquired using scanning sonar (bathymetry) and terrestrial laser scanning (topography).
- Water surface elevation and slope acquired using differential GPS mounted on the boat or on an attached float.
- River discharge measured periodically using an Acoustic Doppler Current Profiler (ADCP).
- Measurements of river width from terrestrial laser scanning or other methods

In addition to these boat-based measurements, collection of ground-based datasets is necessary to improve understanding of SWOT phenomenology. These may include vegetation height, density, and canopy closure from cameras and/or airborne LiDAR, soil moisture and roughness, grain size of channel bed and banks, wind, and the presence of human structures. Observations of land surface characteristics from other satellite altimeters may also be useful for quantifying vegetation and land surface characteristics.

5.2 Research Experiments

The first experiments recommended by workshop participants will focus on using AirSWOT and BoatSWOT observations to demonstrate the viability of the discharge algorithms described here and assess the ability of SWOT to accurately characterize inundation extent and water surface elevation. These experiments, already in the planning stage, will likely take place on the Sacramento River, California during the first half of 2013. Among the key problems to be addressed is determination of the number of overpasses required to accurately estimate discharge and baseflow depth.

Date	Location	Purpose
2013	Sacramento River, CA, USA	Test Durand et al. discharge algorithm, understand basic SWOT phenomenology
2014	Seine and Garonne Rivers, France	Understand how algorithms function in estuarine environments, areas impacted by groundwater exchange, and urban environments.
2015	Tanana and Yukon Rivers, AK, USA	Test SWOT retrievals and discharge algorithms in braided rivers.
?	Atchafalaya/Lower Mississippi, USA and/or French Guyana	Understand SWOT phenomenology in floodplains, and how floodplain-river interactions affect algorithms
?	Upper Mississippi or Alaska (?)	Test SWOT retrievals impacted by snow and river ice

Table 1: proposed field experiments related to river discharge

After this initial assessment, AirSWOT/BoatSWOT validation experiments should be performed in a number of different settings, including braided rivers, rivers connected to active floodplains, urban rivers, and tidal environments. These experiments will test the viability of discharge algorithms in a range of morphologic environments and will help characterize the overall discharge error budget. A summary of planned or recommended field experiments related to discharge calculations is summarized in Table 1.

In addition, future non-field-based research activities will help to improve discharge algorithms. Continued advancement in assimilation of SWOT observations into hydrodynamic models will improve the ability of SWOT to provide spatially and temporally continuous discharge estimates. Finally, we recommend development of global datasets of channel roughness coefficients, bathymetry, river width, and discharge measurements through the acquisition of published datasets, analysis of currently available satellite data, and large-scale international collaboration will help to validate discharge algorithms on a global basis.

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