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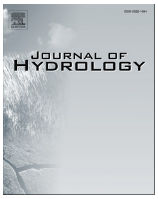

A drifting GPS buoy for retrieving effective riverbed bathymetry

R. Hostache [a,*], P. Matgen [a], L. Giustarini [a], F.N. Teferle [b], C. Tailliez [a], J.-F. Iffly [a], G. Corato [a]

[a] *CRP-Gabriel Lippmann, 41 rue du Brill, L-4422 Belvaux, Luxembourg*
[b] *University of Luxembourg, Faculté des Sciences, de la Technologie et de la Communication, 6 rue Richard Coudenhove-Kalergi, L-1359 Luxembourg, Luxembourg*

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SUMMARY

Spatially distributed riverbed bathymetry information are rarely available but mandatory for accurate hydrodynamic modeling. This study aims at evaluating the potential of the Global Navigation Satellite System (GNSS), like for instance Global Positioning System (GPS), for retrieving such data. Drifting buoys equipped with navigation systems such as GPS enable the quasi-continuous measurement of water surface elevation, from virtually any point in the world. The present study investigates the potential of assimilating GNSS-derived water surface elevation measurements into hydraulic models in order to retrieve effective riverbed bathymetry. First tests with a GPS dual-frequency receiver show that the root mean squared error (RMSE) on the elevation measurement equals 30 cm provided that a differential post processing is performed. Next, synthetic observations of a drifting buoy were generated assuming a 30 cm average error of Water Surface Elevation (WSE) measurements. By assimilating the synthetic observation into a 1D-Hydrodynamic model, we show that the riverbed bathymetry can be retrieved with an accuracy of 36 cm. Moreover, the WSEs simulated by the hydrodynamic model using the retrieved bathymetry are in good agreement with the synthetic "truth", exhibiting an RMSE of 27 cm.

1. Introduction

The cost of damage caused by flooding is highly dependent on the warning time given before an event, making the issuing of timely flood alerts critical for minimizing the cost of flood damage. Predicting floods therefore remains a key concern of our society. Flood inundation models play a central role in real-time flood forecasting. In advanced hydro-meteorological forecasting systems, they provide information about expected flood hazard and damages. The models are used to accurately predict the timing and magnitude of a flood. The utility of any given model is, however, dependent on the availability of the necessary input data. Uncertainties in flood inundation modeling tend to be very high (Pappenberger et al., 2007), despite the physical laws that hydrodynamic models are generally based upon. This is partly a result of numerical approximations within hydrodynamic models, but it mainly derives from inadequate or lacking data on the geometry of the channel and the floodplain, the difficulty in estimating roughness coefficients and the uncertainty in initial and boundary conditions (Smith et al., 2009).

Channel and floodplain topography are required for setting up a hydrodynamic model. While the floodplain geometry can be extracted from freely available topography databases, it is important to mention that there is no database for the world's river bathymetries. The SRTM mission digital elevation model (DEM) for instance covers the Earth surface with a spatial resolution of 90 m. In addition, the Tandem-X mission DEM is expected to provide, from 2014 on, a global surface coverage with a spatial resolution of 12 m. However these data sources are known to have their inherent limitations, especially in narrow valleys and densely populated areas. More accurate elevation data sources like DEMs derived from airborne Lidar techniques can be an alternative for providing floodplain topography, but they come at a cost.

As a global database of river bathymetries does not exist, and because of the necessity to penetrate water for a direct measurement of bathymetry, time and cost intensive field campaigns are generally required.

In this context of lacking riverbed bathymetry data, Durand et al. (2008) and Yoon et al. (2012) showed that river Water Surface Elevation (WSE) measurements from the proposed Surface Water Ocean Topography (SWOT) satellite mission should be helpful for estimating bathymetries using assimilation techniques in hydrodynamic models. Based on a Ka-band SAR interferometer, SWOT will provide gridded WSE information for inland lakes and rivers wider than 50 m. The images provided by SWOT will have a 50 m spatial resolution on 120 km wide swath and the WSE is expected to be measured with a centimeter vertical accuracy over

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[*] Corresponding author. Tel.: +352 470261/417; fax: +352 470264.
E-mail address: hostache@lippmann.lu (R. Hostache).

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a 1 km^2 area (Alsdorf et al., 2007). In the previously mentioned proof-of-concept studies, synthetically generated SWOT observations of WSE were assimilated into the LISFLOOD-FP hydrodynamic model. Durand et al. (2008) were able to estimate bathymetry in five locations along the Amazon river with an accuracy of 56 cm using the ensemble Kalman filter. Yoon et al. (2012) made use of the local ensemble batch smoother (LEnBS) assimilation scheme and were able to estimate the bathymetry with a 52 cm reach average accuracy for the Ohio river after assimilating 8 virtual SWOT revisit cycles. SWOT is foreseen to be launched in 2020. This paper introduces an alternative technique, based on GNSS.

At present, only a limited number of research studies have investigated the potential of GNSS like GPS for WSE measurements. GNSSs are currently mostly used for monitoring sea level (Hong et al., 2008; Watson et al., 2008; Bisnath et al., 2003). Bisnath et al. (2003) found that real time kinematic (RTK) carrier phase is able to provide tide level estimates with a vertical accuracy of 10 cm. Moreover, Holtschlag and Aichele (2001) deployed drifting buoys equipped with GPS in order to investigate flow patterns and describe turbulent dispersion characteristics within river reaches. More recently in a case study on the river Mekong, Apel et al. (2012) showed that moored GNSS equipped buoys were able to provide WSE measurements with an accuracy of 2 cm.

In the light of these encouraging results and with the advent of advanced GNSS, such as Galileo, and with correction information (Differential GNSS) from networks of fixed stations becoming more readily available in near-real time, GNSS-supported measuring devices can be considered a promising alternative for obtaining WSE and flow velocities at a large number of locations.

Furthermore, over the last years, there has been a significant progress with respect to the integration of distributed hydrometric data with hydrodynamic models (e.g. Neal et al., 2007; Andreadis et al., 2007; Matgen et al., 2010; Hostache et al., 2010; Giustarini et al., 2011; Biancamaria et al., 2011).

In such data assimilation studies, modeled state variables or model parameters are sequentially verified and updated via measurements. The idea behind this is to merge the high temporal and spatial resolution of generally rather poor model predictions with more accurate but intermittent remote sensing observations to yield the best possible model simulations. Furthermore, if integrated with parameter estimation techniques, there is the potential to estimate uncertain model parameters, which may be used to increase the accuracy of the model (Montanari et al., 2009). Data assimilation techniques based on different versions of the Kalman filter have been used to assimilate ground gauge-based river level data at points along river reaches (Madsen and Skotner, 2005; Neal et al., 2007) from which discharge can be estimated through state augmentation. Despite this potential, applications of assimilation techniques with distributed stage data continue to be rare. In one of the few studies of this type, Andreadis et al. (2007) successfully used a square-root ensemble Kalman filter to assimilate synthetic WSE measurements from the proposed SWOT satellite mission with simulations from a hydrodynamic model for estimating river discharge. This study showed that the assimilation of 8 successive SWOT overpasses allowed a reduction of the relative error of discharge estimations from 23.2% to 10%. Lai and Monnier (2009) and Hostache et al. (2010) applied a variational data assimilation method using distributed WSE in order to combine in an optimal way measurement data and a 2D shallow water model. This assimilation process allowed (1) the identification of optimal Manning friction coefficients and (2) the identification of areas in the floodplain and the channel where frictions are homogeneous. Smith et al. (2009) assimilated distributed data from wireless sensor networks in a parsimonious time series model to produce forecasts with reduced uncertainty. Matgen et al. (2010), and later on Giustarini et al. (2011), demonstrated the usefulness of assimilating via a particle filter WSE derived from satellite SAR images to improve flood forecasts.

In this general framework, the study aims at proposing a synthetic experiment to evaluate the benefit of assimilating GNSS-derived WSE measurements into a hydrodynamic 1D model for effective bathymetry retrievals. It has to be noted here that we defined effective bathymetry in relation with a hydrodynamic model. Indeed we defined in this study the effective bathymetry as the river channel geometry allowing for correctly predicting flood propagation using a given model. As a matter of fact, an effective bathymetry is defined in relation to a given hydrodynamic model with given parameters and simplifications, but the methodology presented is this paper remains generic and can be applied using other hydrodynamic models. Moreover, during this study we made use only of GPS, but the same method can be applied to any other kind of GNSS.

2. Material and methods

This section introduces the design of a GPS buoy and proposes an assimilation technique for effective bathymetry retrievals. Moreover, it describes a synthetic experiment allowing to assess the usefulness of assimilating WSE provided by the buoy into a hydraulic model. In the context of a proof-of-concept study, the main advantage of using synthetically generated data rather than actual measurements is to allow for controlling the errors and their structure. It is important and necessary to demonstrate the efficiency of an assimilation scheme in a controlled environment before it can be applied to actual measurements. Moreover, a synthetic experiment, with known errors, facilitates the identification of advantages and drawbacks of the procedure itself.

2.1. Designing the GPS Buoy

The aim of the GPS-equipped buoy is to provide WSE measurements with sufficient accuracy, in order to enable the retrieval of riverbed bathymetry through data assimilation. Based on the evaluations of Hostache et al. (2009) and more recently Matgen et al. (2010), we define an elevation measurement accuracy of 30 cm as a target value for GPS-derived WSE measurements. The system is composed of a water-proof canoe-box with a transparent hemispheric lid, filled with an integrated dual-frequency GPS, namely the Hemisphere A221^{TM} Smart Antenna. The hemispheric lid is used to limit potential GPS signal perturbations. To protect it from strong shocks during deployment and to ensure its buoyancy and stability, the integrated system is surrounded by a tire (Fig. 1). The two frequencies, L1/L2, of the GPS receiver allow correcting the major part of the positioning errors due to the ionosphere (Kim and Tinin, 2009). In addition, a Post Processing Kinematic treatment is applied to the data in order to reduce bias and noise. For this post treatment we take advantage of the Luxembourg network of permanent GNSS stations (SPSLux). These reference stations, with accurately known coordinates and altitudes, enable the estimation of the correction parameters. The latter can be used to correct the error associated with a rover GPS receiver in differential mode, provided that the rover is not too distant from the reference station (Apel et al., 2012). In case a reference GPS station would not be available, an alternative would be to make use of OMNISTAR (Martinez et al., 2000), that offers a worldwide differential GPS service, based on reference stations, high power satellites and global network control centers (www.omnistar.com).

It is worth mentioning that a hydro-acoustic sensor, such as a sonar or Acoustic Doppler Current Profiler (ADCP) mounted on a buoy, can be considered as an alternative for obtaining riverbed bathymetry. These systems provide a means for directly measuring