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Research papers

Integrating unmanned aerial systems and LSPIV for rapid, cost-effective stream gauging

Quinn W. Lewis *, Evan M. Lindroth, Bruce L. Rhoads

Department of Geography and Geographic Information Science, University of Illinois at Urbana Champaign, United States

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ABSTRACT

Quantifying flow in rivers is fundamental to assessments of water supply, water quality, ecological conditions, hydrological responses to storm events, and geomorphological processes. Image-based surface velocity measurements have shown promise in extending the range of discharge conditions that can be measured in the field. The use of Unmanned Aerial Systems (UAS) in image-based measurements of surface velocities has the potential to expand applications of this method. Thus far, few investigations have assessed this potential by evaluating the accuracy and repeatability of discharge measurements using surface velocities obtained from UAS. This study uses large-scale particle image velocimetry (LSPIV) derived from videos captured by cameras on a UAS and a fixed tripod to obtain discharge measurements at ten different stream locations in Illinois, USA. Discharge values are compared to reference values measured by an acoustic Doppler current profiler, a propeller meter, and established stream gauges. The results demonstrate the effects of UAS flight height, camera steadiness and leveling accuracy, video sampling frequency, and LSPIV interrogation area size on surface velocities, and show that the mean difference between fixed and UAS cameras is less than 10%. Differences between LSPIV-derived and reference discharge values are generally less than 20%, not systematically low or high, and not related to site parameters like channel width or depth, indicating that results are relatively insensitive to camera setup and image processing parameters typically required of LSPIV. The results also show that standard velocity indices (between 0.85 and 0.9) recommended for converting surface velocities to depth-averaged velocities yield reasonable discharge estimates, but are best calibrated at specific sites. The study recommends a basic methodology for LSPIV discharge measurements using UAS that is rapid, cost-efficient, and does not require major preparatory work at a measurement location, pre- and post-processing of imagery, or extensive background in image analysis and PIV.

1. Introduction

The monitoring of river flow is a vital component of scientific and management efforts aimed at assessment of water supply, water quality, ecological conditions, hydrological response, and channel stability. Together with bathymetry, velocity measurements provide the basis for computations of discharge, the primary metric by which river flow is quantified. Velocity has traditionally been measured with mechanical current meters deployed within the flow (Turnipseed and Sauer, 2010). The development and refinement of hydroacoustic instruments, such as acoustic doppler current profilers (ADCP) and acoustic Doppler velocimeters, which can generate data both on velocity and bathymetry, have greatly enhanced measurements of discharge by decreasing the time investment of each measurement and allowing measurements in deep and fast flows (Yorke and Oberg, 2002). Although the use of traditional and hydroacoustic sensors to measure velocity works well in most environments, these instruments do have limitations, including a considerable investment in instrumentation and the cost of labor to deploy this instrumentation, the relative difficulty obtaining accurate data in rapidly changing flow environments, and a minimum depth requirement for sensor deployment within the flow. The development of an inexpensive method to rapidly measure discharge during challenging conditions, including flash floods, shallow flow in small streams or over floodplains, and dangerous high-velocity or contaminated flows, is needed to accurately characterize water quantity over the full spectrum of hydrologic conditions.

One way to address these problems is with non-contact image-based velocity measurements techniques (Tauro, 2016). A common

* Corresponding author at: Indiana University, Department of Earth and Atmospheric Sciences, Bloomington, Indiana, United States.
E-mail address: qwlewis@iu.edu (Q.W. Lewis).

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non-contact method is large-scale particle image velocimetry (LSPIV). Particle image velocimetry was first developed for laboratory studies of fluid motion and yields accurate, quantitative measurement of velocity vectors at many points in a sampling plane or volume simultaneously (Adrian, 2005). Velocity is measured by tracking the movement of particles within the fluid, or in the case of LSPIV, on the fluid surface, across sequential images (e.g. individual video frames) and velocity is derived from the displacement of particle positions between images (Adrian, 1991). In the case of LSPIV, PIV-based measurements of surface velocity measurements are related to the depth-averaged velocity using a correction factor known as the velocity index (Rantz, 1982). When combined with information on flow geometry, the velocity-index relation facilitates estimates of discharge based on measurements of surface velocity.

LSPIV has been utilized previously as a low-cost method to measure discharge in rivers (Muste et al., 2008; Le Coz et al., 2010; Dramais et al., 2011), but thorough assessments of accuracy and consistency over multiple flow conditions are lacking. Creutin et al. (2003), and Dramais et al. (2011) note that repeated discharge measurements with LSPIV require considerably less time than measurements with hydroacoustic instruments, an advantage during floods characterized by rapid changes in discharge. Potential limitations of LSPIV velocity measurements include dependence on lighting conditions and tracer particle properties (Creutin et al., 2003; Tauro et al., 2016a). Additionally, the value of the velocity index has not been thoroughly analyzed in many field environments yet must be chosen or computed carefully because it can be a major source of error in discharge calculations (Le Coz et al., 2010; Dramais et al., 2011). Although the potential benefits of LSPIV are evident, rigorous testing and continued refinement are needed before the method can be widely adopted by the scientific community.

In concert with the maturation of LSPIV methodology, the commercial availability of Unmanned Aerial Systems (UAS) and the use of these systems in scientific research has dramatically increased over the last several years (Detert and Weitbrecht, 2015; Hugenholtz et al., 2012; Tauro et al., 2016b; Detert et al., 2017; Lewis and Park, 2017). Recently, UAS have been used to map large-scale infrastructure (Siebert and Teizer, 2014), acquire surface topography data (Carrivick et al., 2013 Westoby et al., 2012; Detert et al., 2017), survey biodiversity (Koh and Wich, 2012), and guide precision agriculture (Zhang and Kovacs, 2012). UAS are well suited for use in hostile or dangerous fluvial environments (McGonigle et al., 2008), and can extend applications of LSPIV through greater freedom of movement and more flexible positioning of the imaging device above the surface of the water compared to fixed camera systems. Moreover, video capture can be acquired orthogonal to the river surface, eliminating the need to correct for geometric distortion in oblique images (Tauro et al., 2014).

As UAS continue to increase in reliability, technical capabilities, and ease of use, while simultaneously decreasing in price, their potential use as a low-cost supplement to scientific research is clear. Thus far, the extent to which LSPIV integrated with UAS can be used as an accurate, reliable method for measuring discharge without the need for extensive image processing and analysis has yet to be determined. Although all methods used to measure discharge require basic knowledge of the methodology and operating principles of the instrument (Turnipseed and Sauer, 2010), few studies have produced explicit guidelines and principles on LSPIV discharge measurements obtained from UAS.

The purpose of this study is to evaluate the accuracy of LSPIV discharge measurements derived from imagery of the water surface obtained from a fixed tripod and UAS, achieved through a detailed comparison among LSPIV, hydroacoustic, current-meter, and gauged discharge measurements at multiple field sites. UAS LSPIV datasets are compared to tripod-mounted camera LSPIV datasets to assess the differences between fixed and mobile camera platforms. The potential complicating effects of important setup parameters, including: 1) UAS flight height; 2) camera unsteadiness; and 3) tripod and camera leveling, are analyzed. Next, the potential complicating effects of important processing parameters, including: 1) image sampling length and frequency; and 2) PIV interrogation area (IA) size, are also investigated. An additional focus of the study is the computation and comparison of velocity index coefficients for obtaining depth-averaged velocity among multiple field sites. The study introduces a basic methodology for LSPIV discharge measurements using UAS that is rapid, cost-efficient, and does not require major preparatory work at a measurement location, pre- and post-processing of imagery, or extensive background in image analysis and PIV.

2. Methods

2.1. Study sites and experimental setup

Thirteen paired LSPIV and in-channel measurements of discharge (Q) were obtained at ten different road bridges over streams and small rivers in East-Central Illinois, USA (Table 1, Fig. 1). These sites were chosen from basic inspection of aerial imagery in Google Earth to ensure the bridges were safe to work on, dense tree cover would not impede UAS flights, and the stream was not too wide or complex (e.g. anabraching or containing in-stream wood) to measure with a small field team. Stream gauging stations operated by the United States Geological Survey (USGS) were located at two of the sites. Measurement campaigns were mounted on an impromptu basis in response to rainfall events both to document different flow conditions and to evaluate the rapid-response potential of the method. Supplementary LSPIV measurements were performed on 2017/06/22 and 2017/08/14 (S1 and S2) to study the effects of camera setup and LSPIV processing on resultant velocity and discharge. Channel widths ranged from 4 to 30 m during time of measurement and average flow depths ranged from a few centimeters to about two meters.

Pine shavings manufactured for use as horse bedding served as seeding material for the LSPIV surface velocity measurements. This inexpensive, ecologically inert, and biodegradable wood material provides sufficient contrast against the dark water surface and closely tracks the flow of surface water. A fixed, tripod-mounted camera and a UAS-mounted camera were used to record videos of the water surface and track the movement of particles. The fixed camera was a GoPro Hero4 mounted on a heavy-duty steel tripod placed on the bridge. The UAS camera, an unmodified component of an off-the-shelf DJI Phantom 3 Professional Quadcopter, was mounted on a stabilizing gimbal and operated by the remote pilot flying the UAS. The GoPro camera was contained in waterproof housing and was operated remotely via a real-time smartphone app. Both cameras recorded in 4 K resolution (3840×2160 pixels) at 30 frames per second. To allow for calibration of pixel distance to actual distance during analysis of the footage, two points a known distance apart must be visible within the field of view of the camera. A wooden stake topped with brightly colored duct tape was installed on each bank and the distance between two stakes was measured to the nearest centimeter. The transect delineated by these endpoints was oriented roughly perpendicular to the flow direction based on visual alignment by the field crew.

The alignment of the fixed and mobile cameras was adjusted either manually or automatically to ensure a perpendicular or nearly perpendicular orientation of the optical axes of these instruments in relation to the water surface. The motorized gimbal on the