 DOI 10.1051/lhb/2016002

Estimation of flow discharge by an airborne velocimetry system

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ABSTRACT. – A low-cost airborne velocimetry system has been developed and tested, consisting of an action cam, a quadrocopter, ground reference points, and seeding material. The obtained video frames were ortho-rectified and geo-referenced by computer vision techniques, with the by-product that each image got scaled as well. Flow velocity vector fields were determined using a particle image velocimetry algorithm covering a total reach length of 310 m. The data generally confirm depth-averaged velocity profiles obtained by a 3D acoustic Doppler current profiler. Flow discharges are estimated from that. For areas with homogeneous flow conditions we conclude that a correction factor of 0.85–0.9 should be applied to reduce surface velocities to depth-averaged velocities.

Key-words: flow discharge, image processing, quadrocopter, seeding, surface velocimetry

Estimation du débit d´une rivière par un système vélocimétrie aéroporté

RÉSUMÉ. – Un système de vélocimétrie aéroporté bon marché, composé d'une action cam, d'un quadricopter, de points de référence au sol et d'ensemencement, a été développé et testé. Les images vidéo obtenues ont été ortho-rectifiées et géoréférencées par des techniques de vision informatiques. Sur cette base, des vecteurs de vitesse d'écoulement ont été déterminés sur une portée totale de 310 m utilisant un algorithme de vélocimétrie d'image de particule (PIV). Les données acquises confirment généralement des profils de vitesse moyenne sur la hauteur obtenus par ADCP 3D. Une estimation des débits en est tirée. Pour des zones à écoulement homogène nous concluons qu'un facteur de correction de 0.85-0.9 devrait être appliqué aux vitesses en surface mesurées par PIV pour en déduire des vitesses moyennées sur la profondeur.

Mots-clés : estimation de débit, traitement d'image, quadricoptère, ensemencement, vélocimétrie de surface

I. INTRODUCTION

In recent years, image-based methods get used increasingly in the field of hydraulic engineering [Adrian, 2005; Lüthi *et al.*, 2005]. For field measurement techniques the focus is mainly on estimating the flow discharge. Here, one challenge is to provide an adequate view to a relevant area of interest [Muste *et al.*, 2008; Hauet *et al.*, 2008; Dramais *et al.*, 2011]. Also helicopter-based surface image velocimetry was already successfully applied to estimate the flow discharge during floods [Fujita and Hino, 2003; Fujita and Kunita, 2011]. In line with this research, [Detert and Weitbrecht, 2014] showed that even spatial highly resolved flow measurements from helicopters are possible, when the orthorectification of the images is carried out automatically. Lately, [Pagano *et al.*, 2014] have shown that lightweight action cams in combination with Unmanned Aerial Vehicles (UAVs) apply to measure surface velocities. However, a standard method to record high quality UAV-based video recordings to get detailed insight into river hydraulics is still missing.

To close this gap we have developed and tested a low-cost airborne velocimetry system consisting of an action cam, a low cost quadrocopter, Ground Reference Points (GRP), and seeding material [Detert and Weitbrecht, 2015]. In the following its ability to estimate large-scale surface velocity fields are described and flow discharges are derived from that.

II. EXPERIMENTAL SETUP

II.1. Airborne Video Recordings

Measurements were conducted at Eggrankkurve, Thur River, Switzerland, located at 47.589 N and 8.650 E. Figure 1 gives a survey to the area, where single fields of view of characteristic boundary frames are plotted – as observed during the measurement flights. In total five flights were conducted (M1T1, M2T1, M3T1, M3T2, M4T1), each lasting between 1.5–3.5 min, and each with the focus to a single area with several GRPs on both sides of the river, respectively. The GRPs were located by terrestrial surveying via a *Leica GPS 1200*. The flow was seeded with tracer particles of spruce wood chips with dimensions of 60×60 mm² and a thickness of 2–3 mm.

II.2. Quadrocopter and Camera

Video recordings were realized by a *GoPro Hero 3+ black Edition* whose cost is € 400 (January 2015). The camera

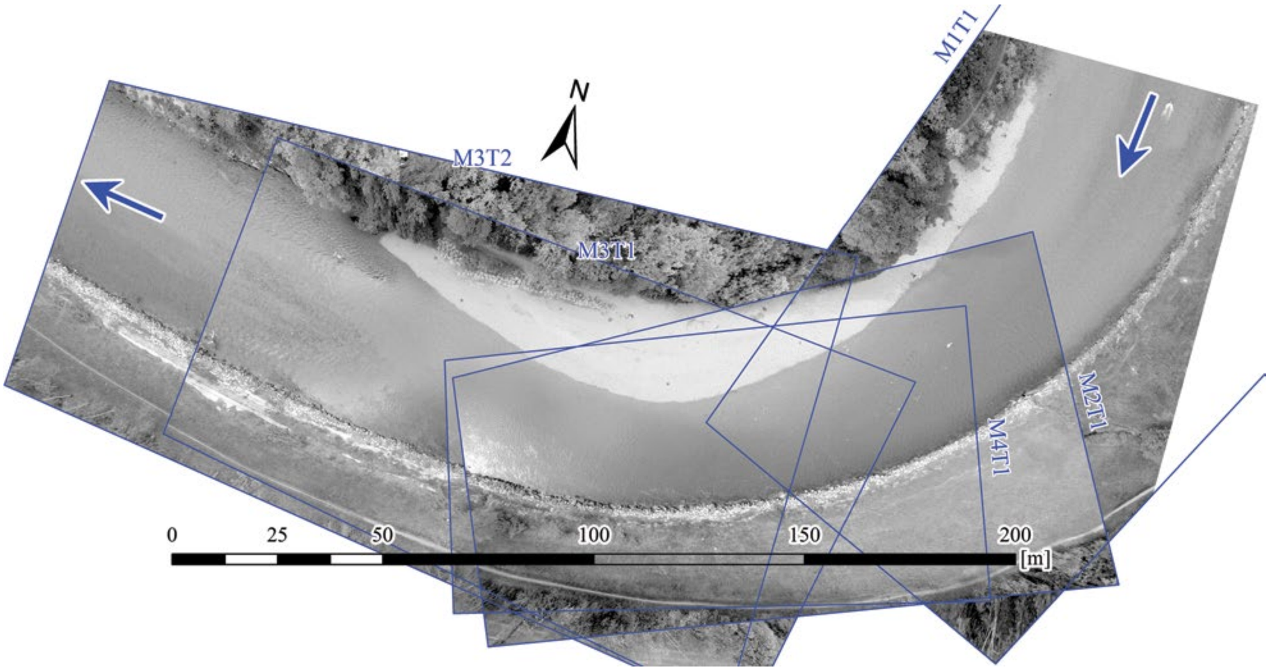

Figure 1: *Map of Eggrankkurve, Thur River, with fields of view of five single characteristic video frames as observed during different measurement flights.*

setting has a resolution of 4096×2160 px^2 and a frame rate of 11.988 Hz.

The UAV used was a *DJI Phantom FC40*. It was slightly modified by inserting batteries with higher performance, by adding a flight recorder *Flytrex Core V1*, and by mounting a vibration damping kit between camera and quadrocopter. No gimbal was used in the setup to keep the flight weight low and, consequently, the flight duration as long as possible. Typically, one flight was limited to ~6 min due to the capacity of the LiPo accu. The price of the entire UAV-system is € 400 (January 2015).

III. VIDEO PROCESSING

The video frames were orthorectified by the use of riparian GRPs and object-detected by computer vision techniques, with the by-product that each image got scaled as well. The GRPs' coordinates were estimated on all frames by affine geometric transformation based on matched points from the Speeded-Up Robust Features (SURF) scheme, a point feature matching technique of [Herbert *et al.*, 2008]. Geo-referencing of each frame was performed by projective transformation to northing and easting coordinates (m) based on the GRPs' coordinates pairs in frame (local) and world (Swiss grid) coordinates. Computations were performed by using the software package MATLAB (Mathworks). Figure 2 gives an example in which the blend of two images mainly shows the tracer movement due to the flow before and after stabilization.

IV. SURFACE FLOW FIELD

Flow velocities were determined based on the geo-referenced images using a Particle Image Velocimetry (PIV) algorithm. The MATLAB-based open source software *PIVlab* by [Thielicke and Stamhuis, 2014] was used to calculate the velocities. Figure 3 gives a geo-referenced survey to the entire time-averaged PIV field within a total reach length of 310 m. To facilitate interpretation, the related streamlines are plotted additionally. Both a distinct flow concentration toward the outer bend as well as the location and dimension of the flow separation along the inner bend become obvious.

V. DISCHARGE ESTIMATION

Figure 4 comprises depth-averaged velocity profiles obtained by a 3D Acoustic Doppler Current Profiler (ADCP, *SonTek River Surveyor M9*) and compared with surface velocity data extracted from the PIV results. Both profiles show the velocity component $(U^2+V^2)^{1/2}$ that is perpendicular to the related profile x, with U being easting velocity and V being northing velocity, respectively. Furthermore, Fig. 4 gives the water depth h determined by the ADCP. Flow discharge can be estimated via

$$Q = \int \sqrt{(U^2 + V^2)}\, h \, \mathrm{d}x. \tag{1}$$

Unfortunately, the PIV system only gives information on the surface velocity – in contrast to the depth-averaged velocity gained by the ADCP. Therefore, using the PIV results leads to some shortcomings when determining the discharge. To inspect these uncertainties the residual deviation from the discharge Q_{Gauge} measured at a nearby gauging station via was defined as

$$r_i = {Q_{Gauge}}/{Q_i}, \tag{1}$$

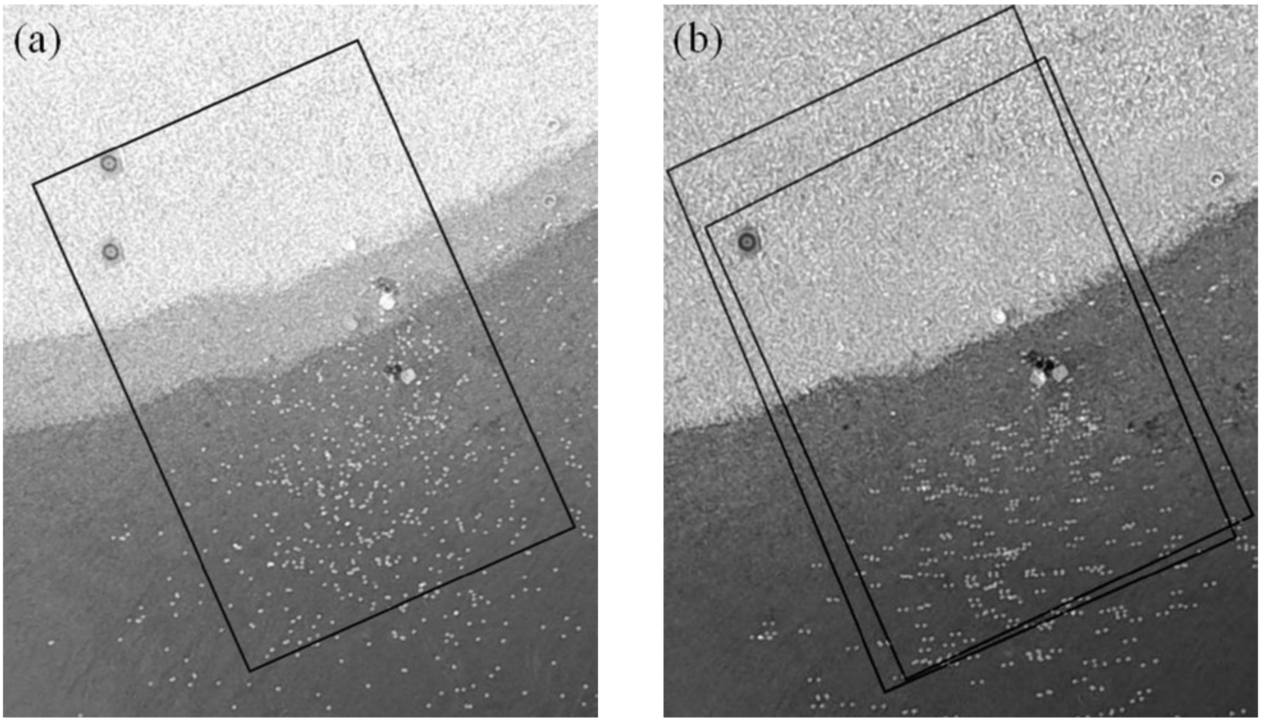

Figure 2: *Blend of cut-out frames (time shift 0.5 s); (a) before video stabilization, (b) after video stabilization.*

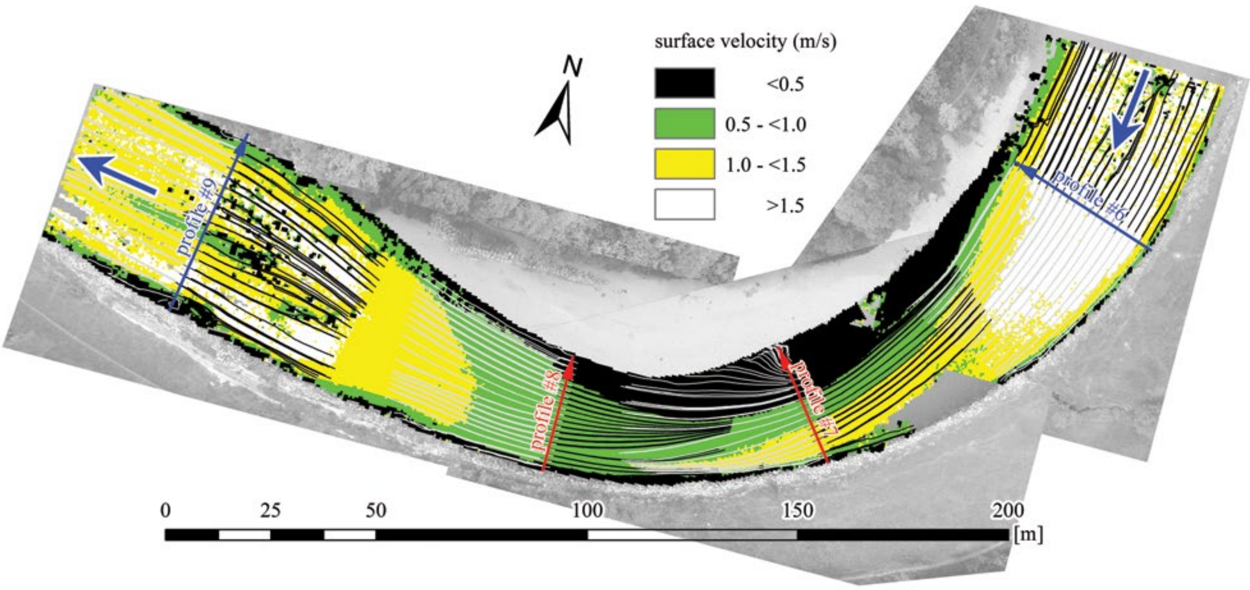

Figure 3: *Time-averaged surface velocity field with raster resolution of PIV results of 1.0×1.0 m² and 50% overlap; the geo-locations of profiles #6–9 are indicated with arrows.*

with index i denoting Q_i determined via ADCP and PIV measurements, respectively. However, it has to be kept in mind that the data from the gauging station and its rating curve are subjected to errors as well. Furthermore, the gauging station is located 4.4 km upstream of the current measurement area at Eggrankkurve. Therefore, Q_{Gauge} is recast to the situation at Eggrankkurve by assuming a time delay of 1 h, i.e. a bulk flow velocity of 1.22 m/s. Hence, during the measurement campaign the 'true' discharge is expected to decrease from 36.0 m³/s at 1:00 p.m. to 33.5 m³/s at 9:00 p.m.

Table 1 summarizes the results for both Q_i and r_i at the different cross-sections #6 – #9 indicated in Fig. 3. In total, the discharge determined via the ADCP confirms the discharge measured by the gauging station. The standard deviation $\sigma(r_{ADCP})$ is only 1%. The ratio of Q_{Gauge}/Q_{PIV}, i.e. r_{PIV}, is between 0.88–0.99, indicating that the crude assumption of the surface velocity being equal to the depth-averaged

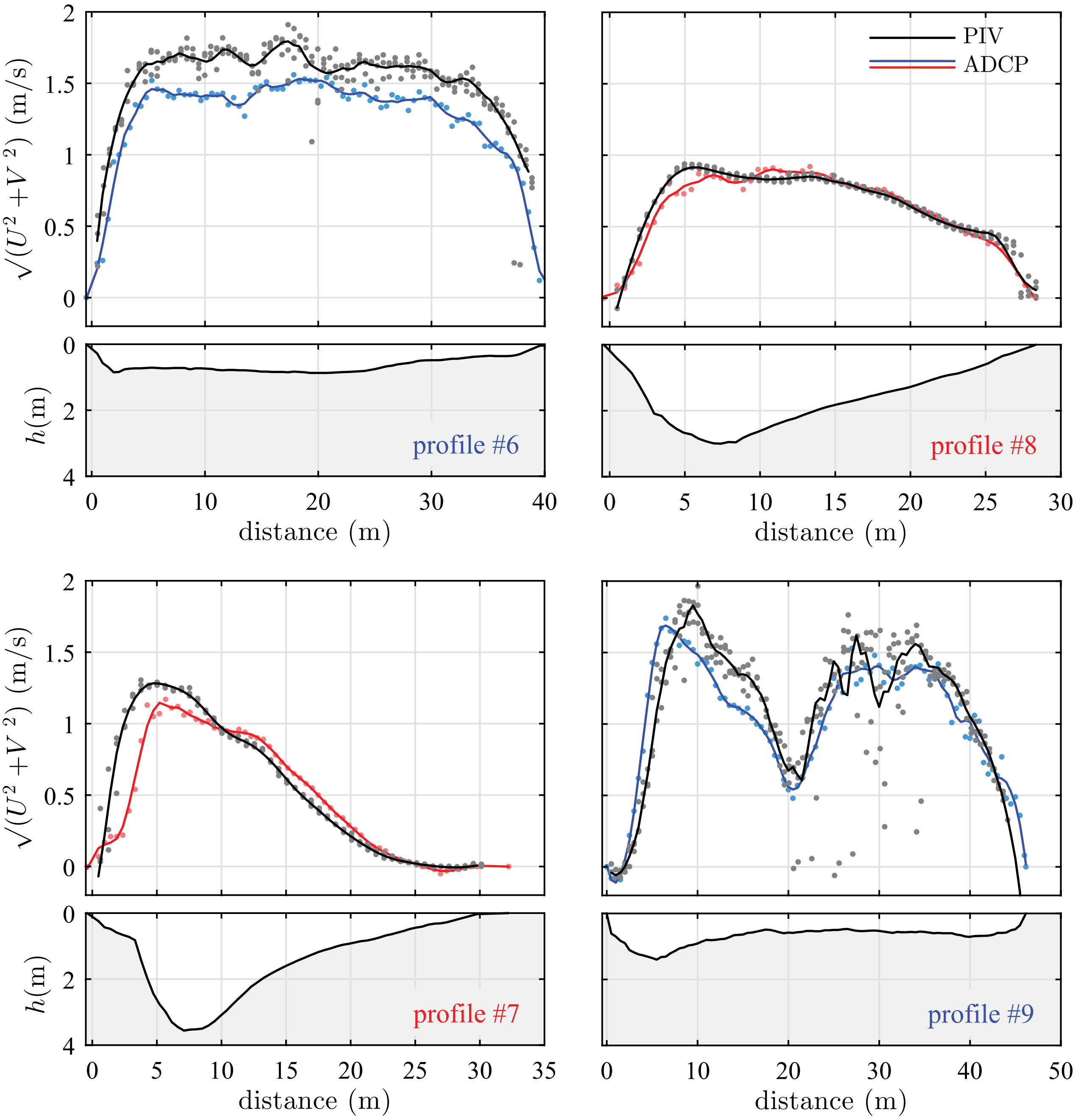

Figure 4: *Comparison of mean velocity profiles projected perpendicular to profile lines gained by a 3D ACDP (depth-averaged velocity) and by surface PIV (points: raw data, lines: scattered data points smoothed by Savitzky-Golay filtering), as well as related water depth profiles; time shifts between ADCP and PIV recordings are given in Tab. 1.*

Table 1: Comparison of Q and r_i, geolocations of profiles: see Fig. 3.

Profile	ADCP				PIV			
	Time (h:min)	**Q_{ADCP} (m³/s)**	**Q_{Gauge} (m³/s)**	**r_{ADCP} (-)**	**Time (h:min)**	**Q_{PIV} (m³/s)**	**Q_{Gauge} (m³/s)**	**r_{PIV} (-)**
#6	17:30	34.3	34.6	1.01	15:00	40.3	35.3	0.88
#7	18:15	34.7	34.4	0.99	[16:45,17:30;18:15]	36.8	~34.5	0.94
#8	19:00	34.5	34.1	0.99	[16:45,17:30;18:15]	35.5	~34.5	0.97
#9	19:45	34.4	33.9	0.99	17:30	34.7	34.5	0.99

DOI 10.1051/lhb/2016002

velocity overestimates the discharge for the current profiles. A typical value for r_i found in literature is 0.85, with values of 0.9 for larger water depths, and 0.8 for lower water depths [Creutin, 2003]. Lately, Dramais *et al.* [2011] found smaller values of r_i of 0.72–0.79 for a gravel bed river with bed slopes of 0.5–6.0%. Thus, $r_{iPIV} = 0.88$ found at profile #6 in the current study confirms literature r_i values for low land rivers (here: bed slope = 0.2%). In contrast, the higher values of r_{iPIV} found at profiles #7–9 cannot be verified directly. However, a closer inspection of the flow conditions reveals that they are, unfortunately, dominated by 3D effects due to the river bend. These are misleading when surface flow velocities are used to extrapolate the distribution of the depth-averaged velocities. Thus, r_{PIV} may reach up to 1 in these complex hydraulic conditions, whereas for a homogeneous flow distribution the assumption of $r_{PIV} \cong 0.85$–0.90 leads to a satisfying estimation of the discharge. A more extensive measurement campaign is needed to fully understand the r_{PIV} variety, however.

VI. CONCLUSIONS

Airborne image-based velocimetry, especially in combination with UAV, gives a high-potential tool for data acquisition in the field. Even the low-cost setup used during our measurements enabled insight to larger surface velocity fields with a reach length of over 310 m. In case river bed profiles are available, flow discharges can be estimated directly. For this purpose we recommend to use profiles with homogeneous flow conditions, and, in case of similar hydraulic conditions to our test case, a correction factor of 0.85–0.9 should be applied to reduce surface velocities to depth-averaged velocities.

VII. ACKNOWLEDGEMENTS

Monitron AG, Switzerland, is gratefully acknowledged for measuring and analyzing the ADCP data and for locating the GRPs by terrestrial surveying.

The authors specifically thank Jürg Trachsel for having assembled and operated both camera and UAV as well as for his further contribution during the field measurements. We appreciate the valuable introduction to UAVs by Maros Bláha (Institute of Geodesy and Photogrammetry, ETH Zürich) and Dominik Smaniotto.

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