Journal of Hydrology 394 (2010) 42–52

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Performance of image-based velocimetry (LSPIV) applied to flash-flood discharge measurements in Mediterranean rivers

J. Le Coz [a,*], A. Hauet [b], G. Pierrefeu [c], G. Dramais [a], B. Camenen [a]

[a] Cemagref, UR HHLY, 3 bis quai Chauveau, CP 220 F-69336, Lyon Cedex 09, France
[b] EDF-DTG, CHPMC, 62 bis rue Raymond IV, BP 875 F-31685, Toulouse Cedex 09, France
[c] Compagnie Nationale du Rhône, LHM, 4 rue de Châlon-sur-Saône F-69007, Lyon, France

ARTICLE INFO

Keywords:
Flash-flood
Hydrometry
Discharge measurement
Image analysis
LSPIV

SUMMARY

Flash-floods that occur in Mediterranean regions result in significant casualties and economic impacts. Remote image-based techniques such as Large-Scale Particle Image Velocimetry (LSPIV) offer an opportunity to improve the accuracy of flow rate measurements during such events, by measuring the surface flow velocities. During recent floods of the Ardèche river, LSPIV performance tests were conducted at the Sauze–Saint Martin gauging station without adding tracers. The rating curve is well documented, with gauged discharge ranging from 4.8 $m^3 s^{-1}$ to 2700 $m^3 s^{-1}$, i.e., mean velocity from 0.02 $m s^{-1}$ to 2.9 $m s^{-1}$. Mobile LSPIV measurements were carried out using a telescopic mast with a remotely-controlled platform equipped with a video camera. Also, LSPIV measurements were performed using the images recorded by a fixed camera. A specific attention was paid to the hydraulic assumptions made for computing the river discharge from the LSPIV surface velocity measurements. Simple solutions for interpolating and extrapolating missing or poor-quality velocity measurements, especially in the image far-field, were applied. Theoretical considerations on the depth-average velocity to surface velocity ratio (or velocity coefficient) variability supported the analysis of velocity profiles established from available gauging datasets, from which a velocity coefficient value of 0.90 (standard deviation 0.05) was derived. For a discharge of 300 $m^3 s^{-1}$, LSPIV velocities throughout the river cross-section were found to be in good agreement (±10%) with concurrent measurements by Doppler profiler (ADCP). For discharges ranging from 300 to 2500 $m^3 s^{-1}$, LSPIV discharges usually were in acceptable agreement (<20%) with the rating curve. Detrimental image conditions or flow unsteadiness during the image sampling period led to larger deviations ranging 30–80%. The compared performances of the fixed and mobile LSPIV systems evidenced that for LSPIV stations, sampling images in isolated series (or bursts) is a better strategy than in pairs evenly distributed in time.

1. Introduction

Flash-floods that occur in Mediterranean regions (Gaume et al., 2009) result in significant casualties and economic impacts. Recently, the Gard river flood of 8–9 September, 2002 killed 24 people and damages were evaluated to 1.2 billion euros (Delrieu et al., 2005). The understanding of flood generation and propagation processes requires reliable streamflow estimates throughout the river network, in real-time. Flood warning systems are sometimes based on discharge values whose forecast may be conditioned with real-time measurements for a better evaluation of the hydraulic risk.

The most common method for monitoring discharges consists of measuring the water level and establishing a stage-discharge relationship (so-called rating curve, e.g., Rantz, 1982; Schmidt, 2002) fitted from a set of direct discharge measurements (so-called gaugings). The establishment and update of rating curves require the gauging of the whole range of discharge values, including extreme flows. Unfortunately, due to the lack of gaugings during floods, the rating curves empirically established at existing gauging stations often must be extrapolated to high-flow rates. The accuracy of the extrapolation can be improved by a hydraulic analysis including collection of post-event data and numerical simulation (Lang et al., 2010). However, the errors on extrapolated discharges remain large, resulting in wide credibility intervals associated with flood quantile estimates (Lang et al., 2010). Flood discharge measurements constitute the most important data for improving the rating curves and for addressing this hydrological issue.

* Corresponding author. Tel.: +33 472208786; fax: +33 478477875.
E-mail addresses: jerome.lecoz@cemagref.fr (J. Le Coz), alexandre.hauet@edf.fr (A. Hauet), g.pierrefeu@cnr.tm.fr (G. Pierrefeu), guillaume.dramais@cemagref.fr (G. Dramais), benoit.camenen@cemagref.fr (B. Camenen).

0022-1694/$ - see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2010.05.049

Gauging methods conventionally used are the velocity-area method (e.g., currentmeters deployed from wading rod, boat, or cableway), Doppler profilers, floats, and chemical tracer dilution. A number of problems make such methods highly difficult or impossible to apply to flash floods. The navigation or even the access to the river shore or the bridges are difficult and often dangerous, due to overbank flooding, high velocities and drifts of varied nature. The short time (a few hours) between the rain event and the peak of flash-floods is a heavy logistic problem for the efficient deployment of hydrometry staffs.

Emerging remote flow monitoring systems, especially those based on radar Bragg diffraction (Costa et al., 2006) or on image analysis like Large-Scale Particle Image Velocimetry (LSPIV, Fujita et al., 1998; Creutin et al., 2003; Hauet et al., 2008a; Muste et al., 2008) offer promising potential for improving the quality of flash-flood discharge measurements. These remote techniques provide surface velocity measurements which require a known cross-section geometry and some hydraulic assumptions to compute the discharge. One of the key parameters for discharge calculation is the depth-average velocity to surface velocity ratio (or velocity coefficient), whose value and variability should be determined carefully as it induces a multiplicative, systematic discharge error (Muste et al., 2008). This parameter may show some variability according to the site and flow conditions.

Remote stream gauging techniques such as LSPIV are valuable new hydrometric tools for gauged sites as well as ungauged sites. At a gauging station with a rating curve, the LSPIV technique provides flood discharge measurements on a broader range than conventional techniques. Subsequently, uncertainties of the extrapolated part of the rating curve can be reduced. Flow measurements available at a gauged site should be used to calibrate and validate the hydraulic assumptions which are made to compute discharge from surface velocity measurements. At a non-gauged site, i.e. without a rating curve nor hydraulic data, realistic hydraulic assumptions can be established from the site characteristics to provide new discharge data with reasonable uncertainty.

The application of the LSPIV technique to flash-floods still have to mature to provide reliable flood discharges. A number of error sources were identified (Muste et al., 2008), but experimental tests are missing for assessing their relative contributions to the uncertainty associated to LSPIV discharge measurements in high-flow conditions. Jodeau et al. (2008) presented a case study with a mobile LSPIV system and high-flow conditions during a dam-flushing operation in a mountain river. Due to high suspended-solid concentrations, the artificial seeding of the flow with cornstarch tracers was required to achieve a correct LSPIV analysis. Hauet et al. (2008b) presented a numerical simulator designed to conduct sensitivity studies on the sources of errors of the LSPIV technique, for varying conditions of measurement. This is a most useful direction of work for assessing the uncertainties associated with the LSPIV discharge measurements. However, the assumptions and results of such a simulator must be validated using comprehensive experimental studies in the laboratory or in the field. Some discharge-discharge comparisons were performed by Creutin et al. (2003), Hauet et al. (2008a), Kim et al. (2008), but velocity–velocity comparisons are scarce in the literature: Jodeau et al. (2008) compared LSPIV velocities with velocities simulated using a 2D numerical model, not with measured velocities.

This paper reports and analyzes comprehensive performance tests for assessing and improving the quality of the promising LSPIV technique applied to the measurement of peak discharges of Mediterranean flash-floods. The tests were conducted during recent flood events at the outlet of the Ardèche river, at the Sauze–St. Martin gauging station managed by the Compagnie Nationale du Rhône (CNR). The accuracy of discharges provided by a fixed LSPIV system (Hauet et al., 2008a) and a mobile LSPIV system (Kim et al., 2008; Jodeau et al., 2008) deployed on the same study site was investigated, as well as the accuracy of the surface velocities provided by the mobile LSPIV system. LSPIV velocity and discharge measurements were compared with accurate reference data (concurrent ADCP measurements, well-documented rating curve). From a practical point of view, the study proposes advances on major sources of errors in LSPIV discharge measurements: image sampling strategies, interpolation and extrapolation of missing velocities, determination of the velocity coefficient value and variability.

2. Methods

2.1. Theoretical overview of the LSPIV technique

The principles of the LSPIV technique (Fujita et al., 1998) used in this study are summarized in this section. For a more in-depth review of the principles of LSPIV and its application to riverine environments, the reader may refer to Muste et al. (2008) for instance.

2.1.1. Computation of surface velocities

As a first step of the LSPIV procedure, images of the river surface sampled with a camera or from an existing movie are orthorectified, i.e., perspective distorsion effects are corrected and pixels are georeferenced. This geometrical correction of the pictures is achieved through a 3D plan-to-plan perspective projection (Jodeau et al., 2008). The 11 parameters of the projection are calibrated from a set of Ground Reference Points (GRP) whose coordinates were measured both in the 2D image space and the 3D real space. In orthorectified images, each pixel is georeferenced and corresponds to a constant metric size.

Then, the computation of flow surface velocities is achieved using a classical cross-correlation algorithm (Fujita et al., 1998) applied to each pair of orthorectified images, separated by a given time interval, Δt. Image patterns associated with tracers naturally present at the free-surface of the flow such as boils, surface ripples, vegetal debris, may be traced, like in the present study. Artificial tracers, such as cornstarch chips for instance (Jodeau et al., 2008), may also be injected in the flow to improve the performance of the image analysis. The most likely displacement of the visible tracers is determined as the maximum cross-correlation coefficient computed between two ensembles of gray-scale pixels (interrogation areas, IA, see Fig. 1). For each IA centred on a point $a_{i,j}$ in the first image, the cross-correlation coefficients with the same IA centred at points $b_{i,j}$ in the second image are computed. The points $b_{i,j}$ around each point $a_{i,j}$ are chosen within a search area (SA). The IA should be small enough to preserve the scale of interest in the flow and large enough to include recognizable tracer patterns within it. The dimensions of the SA should be large enough to cover the tracer displacements from $a_{i,j}$ in each direction, and small enough to reduce computational costs.

The process is iteratively conducted for the whole image in a computational grid defined by the positions of the points $a_{i,j}$. Velocity vectors are derived using displacement values divided by Δt. LSPIV analysis conducted on a set of image pairs yields the instantaneous and time-averaged 2D surface velocity fields. As they are the products of a statistical procedure, computed velocity vectors may be erroneous. Post-processing routines for filtering out erroneous velocities may be based on velocity magnitude/direction thresholds, correlation coefficients, or flow continuity analysis.

2.1.2. Computation of discharge

The discharge across the section is computed according to the classical velocity-area method. From a time-averaged LSPIV surface velocity field, velocities are interpolated at the nodes of a gauging profile across the stream along which the bathymetry is known. In