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# Stream discharge using mobile large-scale particle image velocimetry: A proof of concept

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[1] The authors describe a mobile large-scale particle image velocimetry–based system (MLSPIV) that allows real-time visualization and quantitative estimation of instantaneous and averaged flow characteristics at the river free surface with minimum preparation from the banks of the river. High spatial resolution and the remote, real-time, and fully digital nature of MLSPIV make it well suited to work as either a stand-alone instrument, as presented in the paper, or an integrated system in large-scale networks for monitoring ungauged river basins. Preliminary tests with the mobile LSPIV configuration demonstrate that the technique has the potential to efficiently support research and monitoring of riverine systems. Discharge measurements obtained with MLSPIV show good agreement with discharge measured by the U.S. Geological Survey stream gauging station and other measurement methods.

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## 1. Introduction

[2] Accurate measurement of stream discharge rate is fundamental to studies of hydrologic processes. Collecting discharge data requires either constructing special structures such as weirs or taking tedious measurements of in-stream velocities and channel geometries [e.g., *Buchanan and Somers*, 1969]. Recent efforts toward remote, noncontact discharge measurements have led to identification of several new approaches, as documented by *Costa et al.* [2000], *Creutin et al.* [2003], and *Kean and Smith* [2005], among others. However, all of these approaches require convenient access, preparation, and/or maintenance of measurement sites. Furthermore, they are not particularly cost effective if discharge data need to be collected at many points within a basin or if monitoring of an event at an arbitrary location is desired.

[3] In this article, we describe the development of a new instrument that allows quick estimation of discharge in small to medium size streams. The instrument is essentially a camera mounted on the top of a telescopic mast attached to a truck. An integrated computer system controls the camera, takes images of the surface of the streamflow, and estimates the surface velocity and discharge. The truck provides mobility and access to the stream in remote places. Using this system, one can take measurements of discharge at many locations in a small watershed within a short period of time or monitor a flooding event at an ungauged site. Such capabilities are useful for studies motivated by such initiatives as Predictions in Ungauged Basins (PUB) [*Sivapalan et al.*, 2003] or scaling studies of discharge [*Gupta et al.*, 1996, *Gupta*, 2004].

[4] The velocity estimation principle implemented in the device is an adaptation of the particle image velocimetry (PIV) technique widely used in experimental fluid mechanics measurement of flow velocities [e.g., *Adrian*, 1991; *Raffel et al.*, 1998]. The underlying concept of PIV is statistical inference of the flow velocity vector field from an analysis of pattern displacements in successive images recorded at known time intervals. The technique used in this paper is a direct outgrowth of the conventional PIV used for mapping large-scale flow areas and was therefore dubbed large-scale particle image velocimetry (LSPIV) by *Fujita et al.* [1998]. While the image and data processing algorithms are similar to those used in conventional PIV, LSPIV requires image preprocessing to account for effects of illumination and the oblique angle used for imaging the flows in the field [e.g., *Fujita et al.*, 1998; *Bradley et al.* 2002; *Creutin et al.* 2003], steps not required in a controlled laboratory setting where image coverage is much smaller (typically up to 0.04 $m^2$) and strong, artificial (laser) light is used.

[5] LSPIV can provide instantaneous velocity distributions at the free surface of water bodies as large as 1 $km^2$ [e.g., *Fujita and Kaizu*, 1995]. When used in conjunction with river bed topography (independently measured with another instrument) and assumed velocity distribution over the depth, LSPIV can provide estimates of flow discharge. The technique can be assembled to provide continuously real-time estimates of discharge, as recently demonstrated by *Hauet et al.* [2008a].

[6] A mobile LSPIV (MLSPIV) system is useful for measuring velocity distribution over stream cross sections in normal and extreme flow conditions. Whereas most existing river instruments require deployment of boats and

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equipment in the river, MLSPIV can measure velocities nonintrusively with minimum preparation from the river side. Free surface velocity distribution is indicative of the stream hydrodynamics with special importance in studies regarding stream habitat, river restoration, bank stabilization, and stream-hydraulic structure interaction. MLSPIV can provide an efficient monitoring tool for these studies by, for example, comparing free-surface velocity distributions acquired at successive times [*Hauet et al.*, 2008b].

[7] For the locations where the bathymetry is available from previous measurements, such as the location of the gauge sites, MLSPIV may complement existing rating curves for flow conditions outside of those used for calibration (usually normal flow conditions). Data for high flows are often lacking because of difficulties in deploying equipment and danger to personnel during flood events. Measuring discharge during droughts is also of interest because there are no alternative instruments for measurements in slow shallow flow (i.e., below about 30 cm depth). MLSPIV's flexible deployment capabilities and its quickness in conducting the velocity measurements make it also a good option for ungauged sites where the stream bathymetry is known.

[8] Below, we present the mobile LSPIV system we have developed and tested. The system might be of interest to other hydrologists and can be seen as a prototype that a community-based facility could improve upon (e.g., see discussion of hydrologic suite of instrumentation by *Loescher et al.* [2007]). We discuss several design, implementation, and operational issues that are unique to MLSPIV and impact the accuracy of the discharge estimation. While a comprehensive uncertainty analysis of the system performance is beyond the scope of this paper, we discuss the most important factors that should be considered while using the instrument and illustrate the discussion with initial measurements taken in Iowa.

## 2. MLSPIV System Configuration

### 2.1. Instrumentation

[9] Our MLSPIV system comprises an imaging device (video or digital camera) set on a telescopic mast attached to the deck of a full-size four-wheel pickup truck. As illustrated in Figure 1, camera positioning, image capturing control, and image processing are controlled remotely from a laptop computer located in the truck cabin.

[10] Our measurement system sits on a heavy-duty pickup that is equipped with a steel rack to support the foldable mast during transportation, a power generator, an uninterrupted power supply, and two large-capacity batteries. A lightweight hydraulically operated aluminum mast is installed on the truck's deck and can raise the camera 5 m to 14 m above the ground level, thus accommodating various viewing conditions at a measurement site. The electric power for all equipment, i.e., a notebook computer, the camera pan-tilt unit, and the digital camera, is supplied by two batteries charged by the power generator (Figure 1). The second battery is for backup. To mitigate swaying caused by the wind, three guy lines secure the mast after setting it in the operating position.

[11] The image capturing assembly is composed of a digital camera and a pan-tilt unit (PTU) for positioning. The Olympus® C730 Ultra Zoom camera and PTU connect to the laptop computer that controls the PTU, interfaces with the camera to download the images, and then performs image analysis and discharge estimation. The camera records successive images with a preselected time delay (0.8 ± 0.1 s). The operator can select the image resolution from 640 × 480 pixels to 2048 × 1536 pixels. The digital camera outputs JPEG and TIFF file formats. An important consideration when choosing a camera is the support the camera manufacturer provides to developers and nonconsumer users in such areas as documenting electrical interfaces, providing software developer kits (SDKs) and good application program interfaces (APIs), and providing technical support websites. The camera connects to the laptop computer via a USB interface. Given that the maximum length (14 m) of the mast exceeds the length for the USB standard, we used a USB cable extender.

[12] The PTU (Directed Perception model PTU-D46-17) has a maximum payload of 2.5 kg, a pan/tilt resolution of 0.05 degrees, and a pan/tilt response time of 300 degrees/s. The PTU has industry standard RS232 or RS485 serial interfaces, and one can control it using simple ASCII commands. The entire image capturing unit is enclosed in a weatherproof enclosure. The components were assembled in-house such that one can quickly secure the image capture assembly to the top of the mast right before erecting it. Initially, we experienced erratic communications between the laptop and the image capture unit, but these were corrected by moving the power supplies from the image capture unit down to the truck. Thus, the power supply lines are DC and not AC adjacent to the RS232 signal lines. Furthermore, we used low-capacitance, twisted pair, and shielded cables.

### 2.2. Data Acquisition and Processing Software

[13] We developed two programs, the PTU program [*Trivedi*, 2004] which controls the camera and PTU and the LSPIV program [*Hauet et al.*, 2008b] which processes the images and makes a discharge estimation. The PTU is a Visual Basic 6 application that uses the Rye control/software component (OCX) from the Olympus SDK. The Rye OCX provides access to virtually all the camera functions available to the operator through a Visual Basic or Visual C++ program. The PTU program controls the image properties and the options for image capturing: image resolution, image format, color or monochrome options, the number of image pairs to be captured, time interval between two images within a pair, and the time interval between two successive pairs. The PTU program also controls the PTU to obtain the desired view from the digital camera.

[14] The LSPIV program adds the ability to perform the image processing and flow velocity estimation tasks in real time at the measurement site. Figure 2 illustrates the overall image transformation and processing sequence. The software interfaces can check pairs of images transferred from the digital camera, select the parameters needed for geometric transformation, and request the parameters used in calculating the surface velocity fields. The components of the LSPIV program are stand-alone executables, each having a well-defined functionality, i.e., image enhancement, geometric correction, motion estimation, and discharge estimation. The LSPIV executables communicate with each

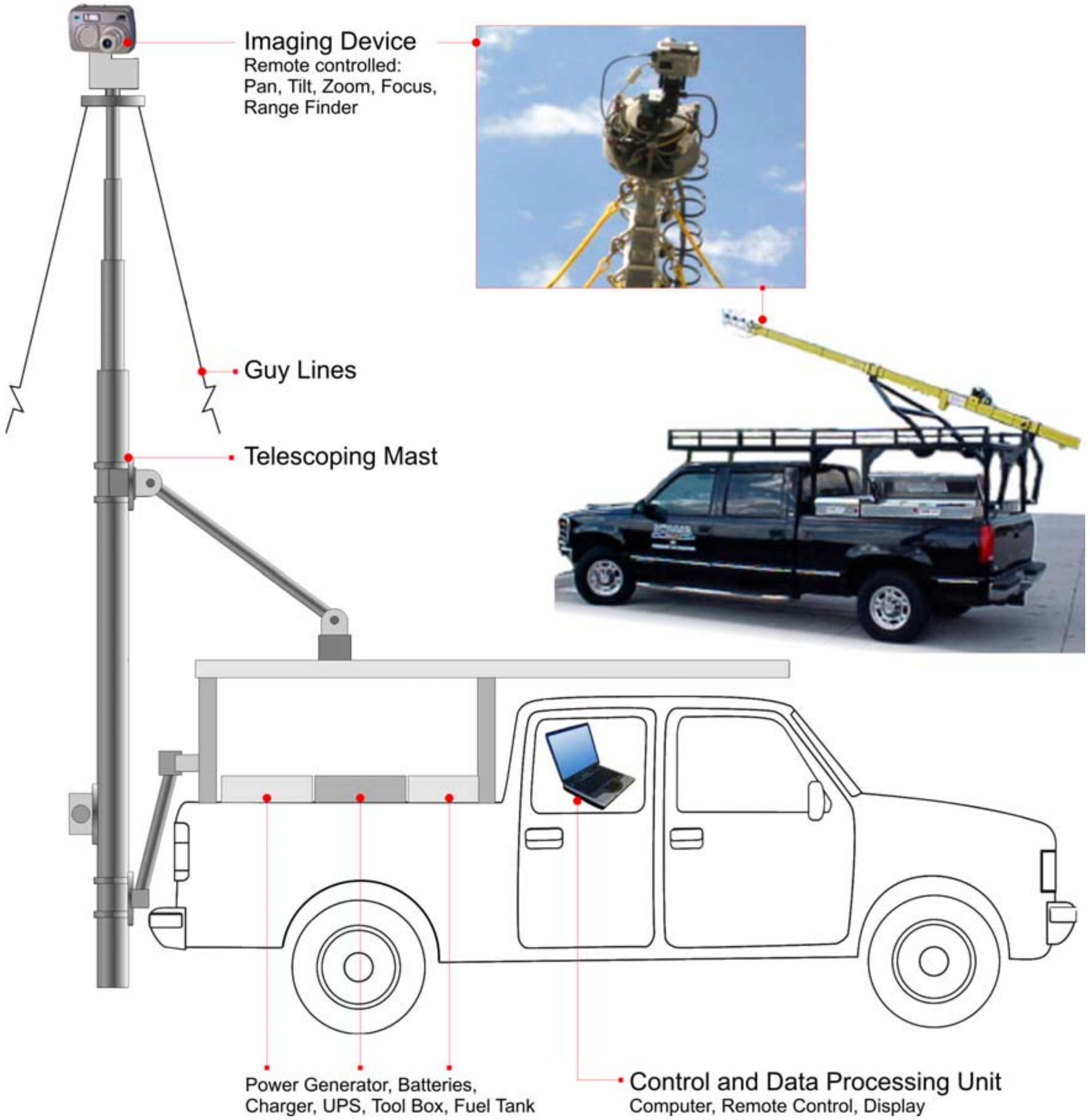


**Figure 1.** Schematic components of the mobile LSPIV system.

other via pipes. The total computation time for an estimation of the velocity field from a 1000 × 1000 pixel image is around 1 min.

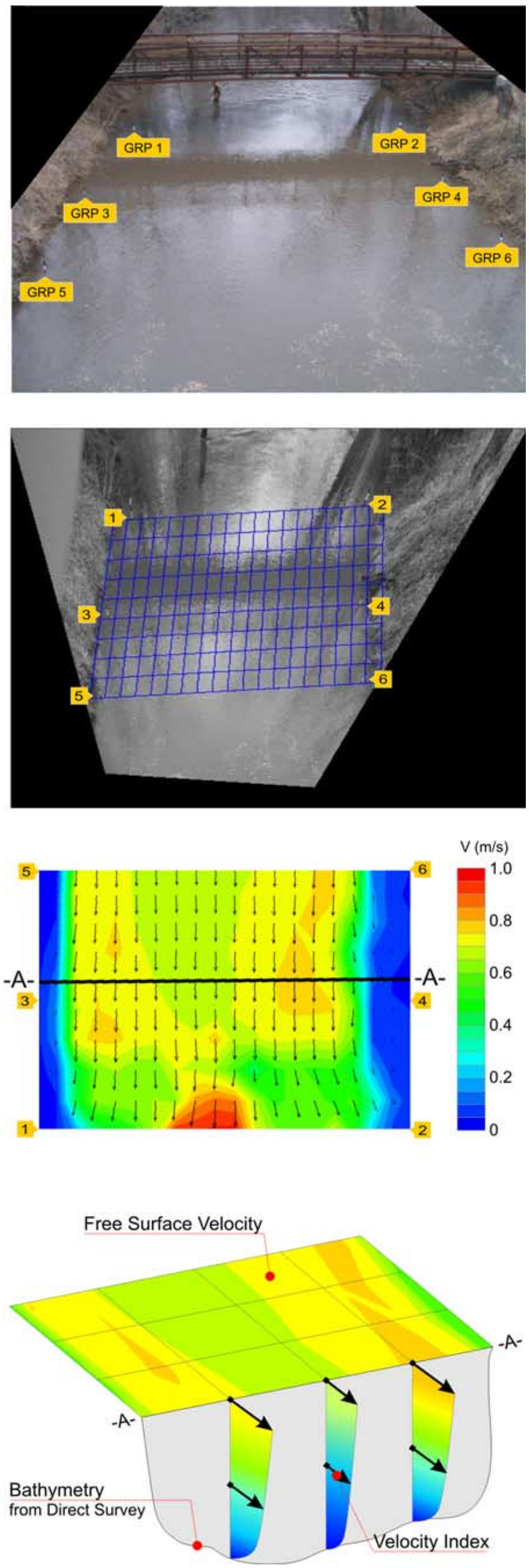
## 3. Measurement Procedures

[15] The measurement procedure consists of the three major steps: (1) setup of the truck and peripherals, (2) camera positioning and image acquisition, and (3) image processing to obtain the velocity fields and discharges. For safety and convenience, at least two people are needed to carry out a measurement with the MLSPIV.

[16] The first step in acquiring data is to approach the site with the MLSPIV truck. The discussion herein assumes that the site is freely accessible; that is, no impediments related to property rights or other obstructive conditions (topographic or vegetation) are involved. Subsequently, the mast with the PTU and camera are deployed which requires a stable and approximately horizontal truck position. Depending on the location and the required height of the mast, use of three guy lines should be considered. In some locations, such as a bridge where parking is allowed, low mast deployment is adequate and the use of the guy lines is unnecessary.

[17] Another element of the setup is defining reference points. Because the camera records images at oblique angles to the flow surface, perspective projection distortion is significant. Applying a geometrical transformation to the image in conjunction with a set of reference points of known locations, corrects for the distortion. The location of reference points can be quickly determined using a total station, which is a standard device used in construction surveying or another equivalent measurement instrument such as GPS. A minimum of four ground reference points (GRP) located in the field of view must be surveyed. For best results, the points should be located near the banks close to the water level, both in the near as well as in the far field (Figure 2). For a more detailed discussion of the mathematics involved in the transformation, see *Creutin et al.* [2003].

[18] The second step entails image acquisition. The fundamental idea behind the PIV technique is detection of



movement of flow tracers in consecutive images. As with laboratory applications of PIV, seeding of the flow with neutrally buoyant tracer particles is often necessary. Sometimes, the field conditions provide "natural" seeding such as foam or floating debris. Natural seeding defines any particular combination of factors that produce visible patterns at the free surface. Use of LSPIV in previous studies illustrated that often time natural seeding (debris or foam floating at the free surface [*Hauet et al.*, 2008a], small waviness of the free surface [*Costa et al.*, 2000]) suffices for LSPIV provided that the image acquisition time is extended to circumvent the possible intermittency and discontinuity in the seeding over local areas in the flow. In the absence of natural seeding, wood chips, leaves or environmental friendly materials can be released upstream the location of the LSPIV measurement. Given the relatively low range of velocities in small and medium rivers (i.e., 1–3 m/s), the off-the-shelf commercial cameras (operating at a rate of 60 video frames per second) can easily capture the displacement of the flow patterns moving in image pairs.

[19] A related issue is illumination. Natural light is used as illumination for LSPIV measurements instead of the laser light used in laboratory experiments. Consideration should be given to the uniform illumination of the imaged area. Of particular concerns are the bright spots due to direct reflections and, at the other extreme, the lack of sufficient illumination. Establishing quantitative thresholds for the two illumination extremes would depend on the camera characteristics, the visibility of the flow pattern and the selection of the processing parameters. A proven practical rule of thumb is that, if the observer can visually detect water surface movement, the image processing software will also detect and subsequently evaluate the velocities at the free surface.

[20] The third step is image processing to estimate the surface velocity distribution. Using standard PIV techniques, a pair of (corrected) images is processed to estimate surface velocity (Figure 2). The images are divided into several interrogation and search areas, and search areas are larger than interrogation areas [*Fujita et al.*, 1998]. Within each search area, pattern correlation coefficients are calculated between two consecutive pairs of images for each interrogation area. The location of the interrogation area with maximum correlation defines the displacement (velocity) vector. Thus, surface velocity vectors can be calculated for the entire field of view with the spatial resolution determined by the size of the interrogation area.

[21] Our image processing software is based on the algorithm developed by *Fujita et al.* [1998] and is conceptually similar to the correlation imaging velocimetry of *Fincham and Spedding* [1997]. Subpixel displacements are computed using a Gaussian fit of the correlation coefficient values of the eight pixels around the maximum correlation coefficient position. Vectors that are erroneous because of the faulty matching of the image patterns are

**Figure 2.** Conceptual sketch of the sequence of steps involved in MLSPIV estimation of discharge: (top to bottom) setting up ground reference points (GPR 1 to GPR 6); transformation from the physical to image plane; surface velocity calculations; and discharge estimation at an arbitrary cross section A-A using the velocity index method.

corrected using an algorithm developed by *Fujita and Kaizu* [1995] that is based on the principle of flow continuity.

[22] In our mobile LSPIV software, the operator has the option of performing all the PIV processing in real time and can view the estimated velocity vectors while still recording more images. This capability allows an operator to make a quick judgment regarding the reasonableness of the results and to make changes to improve the imaging of flows. As a result, before leaving the site, the operator can be confident that the measurements are of sufficient quality. Subsequent application of the LSPIV software to the entire set of recorded images (in an office setting) provides information on both time-average velocity fields and velocity fluctuations.

[23] The last element in the processing is the discharge estimation. The free surface velocity combined with river bathymetry and the appropriate vertical velocity distribution model allows discharge estimation (see Figure 2). The channel bathymetry can be measured prior or during the velocity measurements. If the channel bathymetry is obtained prior to the MLSPIV measurements it is assumed that the bathymetry is not changing in the time period between the discharge measurements.

[24] Surface velocities at several points along the surveyed cross section (Figure 2) are computed by linear interpolation from neighboring grid points of the LSPIV-estimated surface velocity vector field. Assuming that the shape of the vertical velocity profile is the same at each point, the depth-averaged velocity is related to the free-surface velocity by a velocity index. The index velocity is directly related to the shape of the velocity profile, which in turn is dependent on bed roughness (and its relative submergence for large roughnesss elements such as dunes and ribs), Froude number, and channel aspect ratio. The study conducted by *Polatel* [2005] for relative shallow flows over bed roughened with ribs and dunes employing various flow velocities found the velocity index in the 0.79–0.92 range. The available data do not allow, however, to establish a relationship between the geometry and flow conditions and the index velocity. Lacking these relationships, Rantz's value of 0.85 is generally used by the hydraulics community for the index velocity in rivers [*Costa et al.*, 2000]. The discharge for each river subsection is computed following the classical velocity-area method [*Rantz*, 1982].

## 4. Method Accuracy

[25] LSPIV measurement accuracy is affected by elemental errors generated in each step of the measurement process. *Kim* [2006] identified 27 error sources that might affect the LSPIV measurements in field conditions. These error sources were classified according to the measurement phase: illumination, seeding, recording, transformation, processing, or postprocessing. Error sources were also classified on the basis of their effect on velocity estimates. Global errors are constant over the whole image area and affect all the calculated velocities. Local errors can vary from one grid point to another over an image. Errors from different sources depend on each other and on the LSPIV configuration and operating conditions. Consequently, rigorous uncertainty analysis of surface velocity fields and discharge estimates is a complicated task that is beyond the scope of this article. Currently, the authors are summarizing the comprehensive uncertainty analysis to fully document the overall accuracy of the technique and to assess the effect of various environmental and operating conditions on the MLSPIV performance in a separate paper, currently under development.

[26] A preliminary analysis by *Kim* [2006] conducted with a rigorous propagation of the elemental errors to the final estimates for a typical field case shows errors in the velocities ranging between 10 and 35% (at 95% confidence level), depending on where the velocity was calculated over the cross section. For most of the velocities, the errors were within 10% of the reference velocity. As expected, the measurement accuracy is largely dependent on the local measurement environment especially the illumination and seeding conditions. The study by *Kim* [2006] reveals that for the present experiment, conducted in carefully selected measurement conditions, five error sources (tracing, sampling time, distance, GRP identification and seeding density) were most important contributors to the total velocity measurement uncertainty. In lieu of rigorous uncertainty propagation, we evaluated our MLSPIV approach by direct comparison of the discharge estimates to a reference value.

## 5. Case Study

[27] The site selected for testing the MLSPIV discharge measurement capabilities is a cross section of Clear Creek near Coralville, Iowa (Figure 2). MLSPIV was deployed from a bridge over the stream, and the measurement cross section is located 25 m downstream from the bridge where a U.S. Geological Survey gauging station (USGS 05454300) is installed. The stream was about 20 m wide and 0.7 m deep during the measurements. The discharge measured using MLSPIV was compared with a StreamPro ADCP measurement and the estimated discharge from the USGS rating curve. Six ground reference points were surveyed with a total station to obtain the information needed for image transformation. We used wood mulch to seed the flow surface. Images were captured with the digital camera set for a resolution of 1280 by 960 pixels. During MLSPIV deployment, the weather was cloudy with a north wind of 5.8 m/s.

[28] The velocity field obtained using the image capturing device is shown in Figure 2. Using the bathymetric data measured with the StreamPro ADCP for a cross section contained in the imaged area, the discharge was calculated using conventional methods [*Rantz*, 1982]. Conversion of the free surface velocity to depth average velocity was obtained using a 0.85 velocity index. During the MLSPIV measurement, the river stage and discharge reported by the USGS real-time stream data were 1.2 m and 5.2 $m^3$/s, respectively. This USGS discharge was used here as reference for the MLSPIV measurement. The estimated discharge based on 14 image pairs using MLSPIV is 5.1 $m^3$/s, which is in relatively good agreement (−2.0%) with the USGS estimate. The standard deviation of the 14 estimates was about 8%. The estimated discharge using the StreamPro ADCP was 4.9 $m^3$/s, a difference of −5.5%.

## 6. Closing Comments

[29] The mobile LSPIV system we describe in this paper can potentially measure free-surface velocity distribution in small and medium size rivers during normal and extreme

flow conditions during daylight. Using additional information obtained prior to or during the free-surface measurement, LSPIV can estimate stream discharges. The system can take flow data during conditions too hazardous for methods that require immersed equipment (flooding) and in situations where the interior of the flow is, for one reason or another inaccessible or difficult to reach. In these extreme situations, the need for data is greatest for a variety of engineering and scientific applications because of lack of alternative measurement techniques. The system cannot only provide a cost-effective means of estimating discharge at ungauged sites but can also improve rating curves at existing gauging sites during flooding. Because of the relatively short setup time, the system offers a possibility to document the kinematics of flood wave propagation, providing event-based observations that could not be documented before. Proof-of-concepts tests conducted by *Kim* [2006] could capture the loop rating that is indicative of the unsteadiness of the flow in the channel during routing of a storm discharge.

[30] The accuracy of the MLSPIV is relatively good, as demonstrated by the field measurement presented in this paper. The Clear Creek case study illustrates that the measured discharge using MLSPIV differs −2% from the USGS rating curve and 5.5% from concurrent measurement with the StreamPro ADCP. In addition to the acceptable accuracy, MLSPIV is convenient and relatively easy to deploy and operate in comparison with intrusive, boat-based measurements. Consequently, the technique is recommended for measurements of gauged and ungauged sites. A comprehensive uncertainty analysis of the system is outside of the scope of this short communication and will be reported at a later time.

[31] We also have recommendations for improving certain elements of the instrument. If we were to construct another MLSPIV unit, we would include the following improvements: a stiffer (beefier) mast assembly to reduce the sway without the use of guys, wireless control of the camera, a digital inclinometer mounted on the PTU, and markers equipped with a high-accuracy GPS chip. The markers would wirelessly send their exact position to the data acquisition system. Their simple geometry (size, shape) and color would make them easy to identify in the images and thus eliminate the time consuming surveying. All in all though, the instrument is fully functional and ready to support a range of hydrologic and hydraulic studies. While the instrument in the present configuration is not the most accurate among the velocity measurement techniques, it efficiently and rapidly provides results within acceptable uncertainty range for measurement situations difficult or impossible to be dealt with using alternative instruments.

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