A field application of particle image velocimetry (PIV) for the measurement of surface flow velocities in aquatic habitat studies

J.C. Smith, F. Bérubé & N.E. Bergeron

Institut National de la Recherche Scientifique - Eau, Terre et Environnement, Québec, Canada,

e-mail: nbergeron@ete.inrs.ca

ABSTRACT

The spatial distribution of river flow velocities plays a central role in aquatic habitat studies. However, measurement of the required flow velocity information is tedious and time consuming using conventional current meters, particularly when large areas are studied. In this paper, we show the development and use of a particle image velocimetry (PIV) application for the measurement of flow velocity fields in aquatic habitat studies. PIV is an image analysis technique that measures the displacement of an object between two frames and divides the resulting distance by the time interval between the frames. Our PIV application determines surface flow velocity in rivers from oblique digital video records of the water surface. The video images are analyzed with autocorrelation algorithms that use surface water texture to track the displacement of water surface particles between subsequent frames. The resulting velocities in pixels/second are then orthonormalized with total station ground control points to yield real velocities in meters/second. This paper describes the PIV technique and presents the results of a field validation conducted on the Ste-Marguerite River, Québec, Canada. This work showed that surface water flares and visibility of the bed through clear water both induce errors in the PIV measurement. However, these errors can be effectively filtered out, thereby leading to a strong significant relationship ($R^2 = 0.86$, $p < 0.0001$, slope = 1.08, intercept = 2.9 cm/s) between current meter and PIV measured velocities.

Keywords: flow velocity measurement, PIV, habitat.

1 INTRODUCTION

Flow velocity is an important factor in fish habitat selection along with substrate size and water depth [1],[2]. However, the spatial distribution of velocities are particularly time consuming to quantify as each velocity measurement must be averaged over 40-70 seconds to account for temporal velocity variations [3]. This problem becomes especially important when one investigates fish habitat at the riverscape scale [4] with the same spatial resolution as in conventional micro-habitat studies. While there have been many advances in remote sensing techniques to measure grain size [5] and depth [6] which reduce the data acquisition time, there have been few advances in the remotely sensed measurement of velocity in natural rivers. Particle Image Velocimetry (PIV) is an image analysis technique that measures the displacement of an object between two images and divides the resulting distance by the time interval between the images [7]. Creutin *et al.* [8] and Bradley *et al.* [9] have employed particle image velocimetry (PIV) techniques to measure discharge where they made use of anthropogenic structures to mount their cameras. Fujita and Hino [10] affixed a camera to a helicopter and made use of buildings, roads, and bridges to correct the background shifts incurred by the moving helicopter. In most situations, such anthropogenic structures or high terrace banks are not generally available at study sites from which digital records are acquired. Therefore a PIV application that does not necessitate the camera being elevated was needed to characterize fish habitat. This paper describes a new PIV methodology where images are recorded at a very oblique angle from a low riverbank. It then discusses the obstacles to accurate PIV measurements (*e.g.* visible river bed, surface water flares) in such conditions as well as how to overcome them to obtain good surface velocity measurements with this technique.

2 THE PIV TECHNIQUE

The PIV algorithms used in this application track the surface water texture in the images to calculate the displacement between two frames. This displacement is measured using autocorrelation analysis with the following function:

$$\Phi_{cor}(m,n) = \sum_{i=1}^{M}\sum_{i=j}^{N} g_1(i,j)\cdot g_2(i+M, j+N) \quad (1)$$

where g_1 is the image at $t = t_1$ and g_2 is the image at $t = t_1 + \_t$. Processing time for this function was improved by using the following fast fourier transform (FFT):

$$\Phi_{cor}(m,n) = \Re eel\{invFFT(FTT(g_1)\cdot FFT'(g_2))\} \quad (2)$$

The displacement between frames is divided by the time between the two frames to yield a velocity in pixels/second. This process is then repeated for each pair of frames (hereafter referred to as a frame couplet) for the length of the video record. The velocities calculated at each point in the image are then averaged. The resulting velocities are then orthonormalized using four total station ground control points to yield real velocities in m/s.

3 METHODOLOGY

3.1 Study Site and Field Methods

Field validation of the technique was carried out on the Ste-Marguerite River, Québec, Canada (Figure 1) in June 2004. The Ste-Marguerite River is a meandering cobble bed river in the Canadian Shield. Video records of the river were obtained from a 1.5 m high bank for three minutes with a 3-CCD mini-dv digital video camera (Sony VX-1000. 480 x 720 pixels) at 30 Hz (30 frames/second). The river was seeded with biodegradable foam upstream and outside of the camera's field of view to create additional texture at the water surface. Eleven surface water velocities were measured with an electromagnetic current meter (Marsh-McBirney Flow-Mate) for 60 seconds along a transect the width of the river. These velocities were then compared to PIV velocities to determine the accuracy of the method. Four control points were obtained with a Leica TC 307 total station in the camera's field of view.

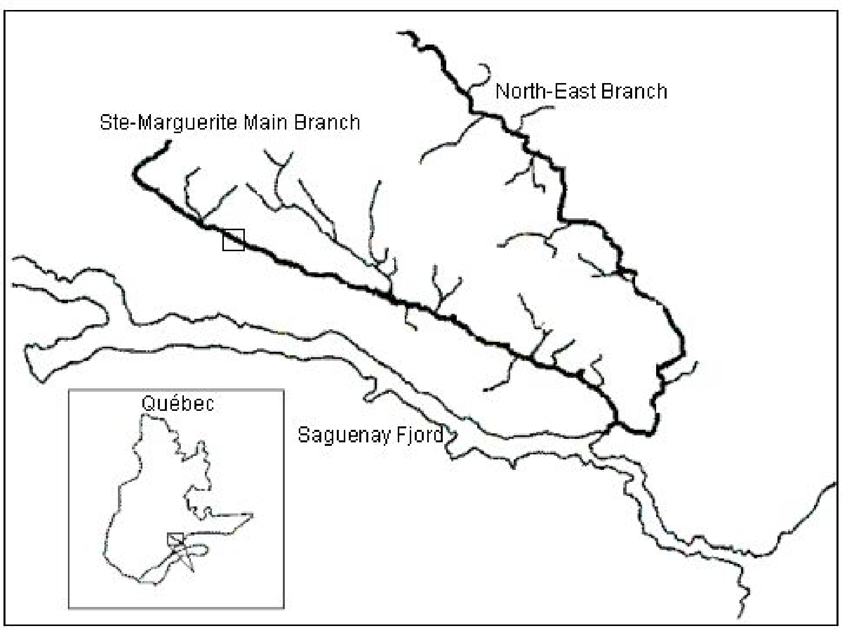

Figure 1. Study area: Ste-Marguerite River, Saguenay, Québec, Canada.

3.2 PIV Analysis

In the laboratory, the video record was transferred to the computer and saved in an appropriate format for processing (Avi file in cinepak compression at 30 frames/second). The video was then processed with MatLab programs using the autocorrelation functions described above to yield a field of velocity vectors in pixels/second. Velocities were calculated between frame couplets with a moving interrogation area of 60 x 60 pixels with an overlap of 40 pixels. Velocities were calculated at a sampling frequency of 10 Hz. The video was processed over 180 seconds. Frame couplet velocities were then averaged for each calculation point. This velocity field was then orthorectified using the 4 total station control points to yield real velocities in meters/second.

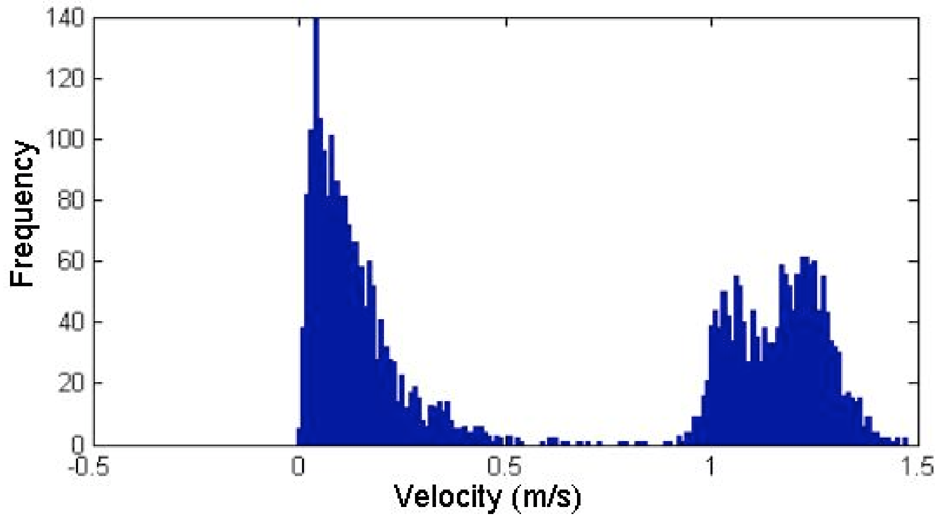

Figure 2. Frequency distribution of frame couplet velocities calculated at one point.

3.3 Error Filtration

Due to the field conditions, unexpected sources of error were encountered. The Ste-Marguerite River is shallower and clearer than previously studied rivers [8],[9],[11]. The riverbed in this case was visible in portions of the image where the river was shallower, and when seeding was insufficient. Velocity calculations were lower at these points because the algorithms occasionally tracked the riverbed at a velocity of 0 cm/s which was then included in the average of the frame couplet velocities. Additionally, there were flares on the water surface that resulted in false velocity measurements. Both types of errors can be seen in the frequency distribution of frame couplet velocities (Figure 2). The peak at 0 m/s results from the effect of seeing an unmoving bed through clear water (hereafter referred to as the bed effect). There is also considerable scatter around the second peak because the algorithms tracked surface water flares that occur in all directions and magnitudes. Furthermore, the use of a one-dimensional current meter to measure velocities made them unsuitable for direct comparison with the PIV measured velocities. A current meter measures only the component of a velocity for the direction in which it is pointed. However the PIV algorithms measure the full magnitude of the velocities, regardless of their orientation.

To isolate and remove the above-mentioned bed effect and flares, polar graphs were used to determine the principal axis of flow (defined as the direction in which a current meter would be positioned to measure velocities) (Figure 3). These graphs were also used to transform the PIV measurements into a format suitable for comparison with the one-dimensional current meter measurements. For each point where velocities were calculated, the principal axis of flow was determined along with an upper and lower limit. The upper and lower limits served to isolate real velocity vectors and exclude flare vectors. All velocities falling within those limits were reprojected onto the principal axis of flow (Figure 4). This served to extract only the component of the vector in the axis of the current meter thereby reducing the magnitude of the vector. The PIV measurements were then processed using these criteria. Figure 5 shows the diminished bed effect (a greatly reduced peak at 0 m/s) and less scatter due to the surface water flares. PIV velocity measurements were then compared with current meter velocities, assuming that the current meter velocities are true measures of velocity. The error in terms of distance from the camera was then examined.

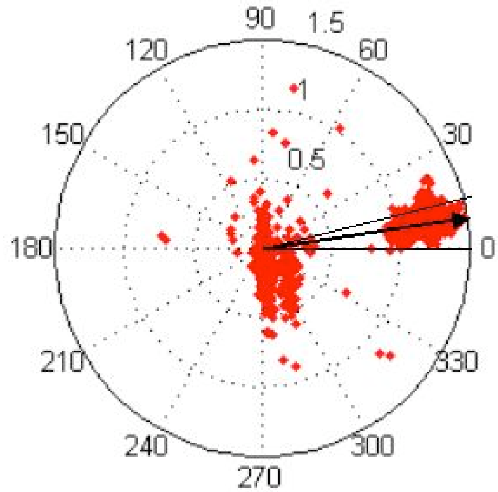

Figure 3. Polar graph showing the frequency, magnitude (m/s), and direction of frame couplet velocities calculated at a single point.

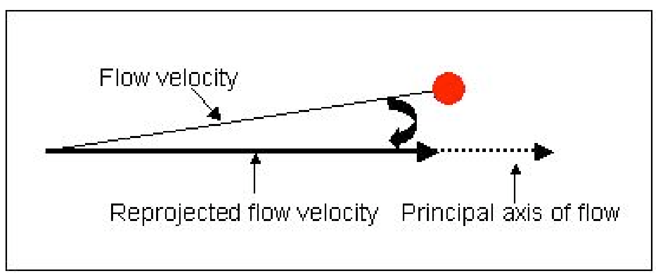

Figure 4. Reprojection of a PIV flow velocity onto the principal axis of flow.

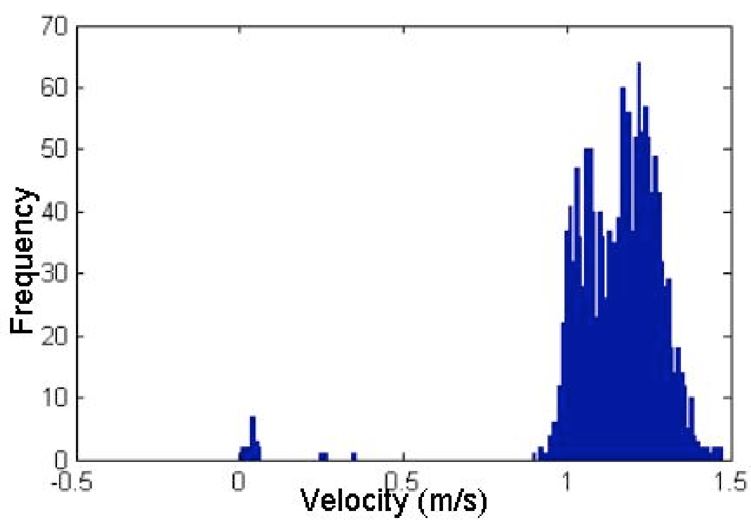

Figure 5. Frequency distribution of frame couplet velocities calculated at one point with the filtered PIV data.

4 RESULTS

PIV measured velocities were plotted against the current meter velocities. The relationship obtained (Figure 6a) was good (R^2 = 0.82, p = 0.0001). However, the PIV method did not yield a slope near one nor a intercept near zero (slope = 1.4, intercept = -30.4 cm/s). If figure 6a is examined in conjunction with figure 6b, which illustrates the error with respect to distance from the camera, a small overestimation until the 15-meter mark is observed, after which velocities are underestimated. This sudden change in the direction of the error could be attributed to the fact that due to the distance from the camera and the correspondingly large area the interrogation area covers; the interrogation area includes the bank beyond this distance thereby diminishing the velocity measurement. We therefore removed these two points to continue the analysis. This resulted in a very strong relationship (R^2 = 0.86, p = 0.0001) between the PIV and current meter velocities (Figure 7). In this case, the slope approached 1 (slope = 1.08) and the intercept was close to zero (intercept = 2.9 cm/s).

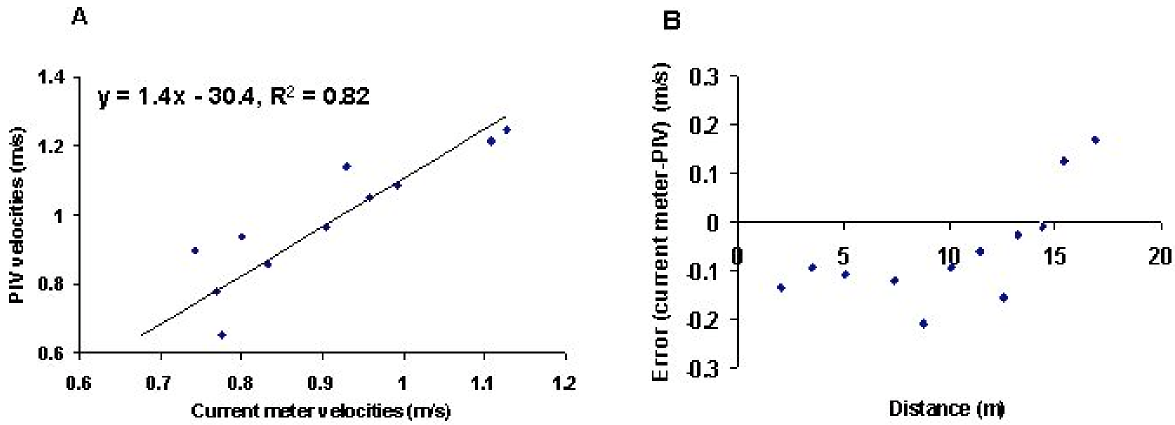

Figure 6. A) Current meter vs. filtered PIV measurements B) Error with distance from the camera.

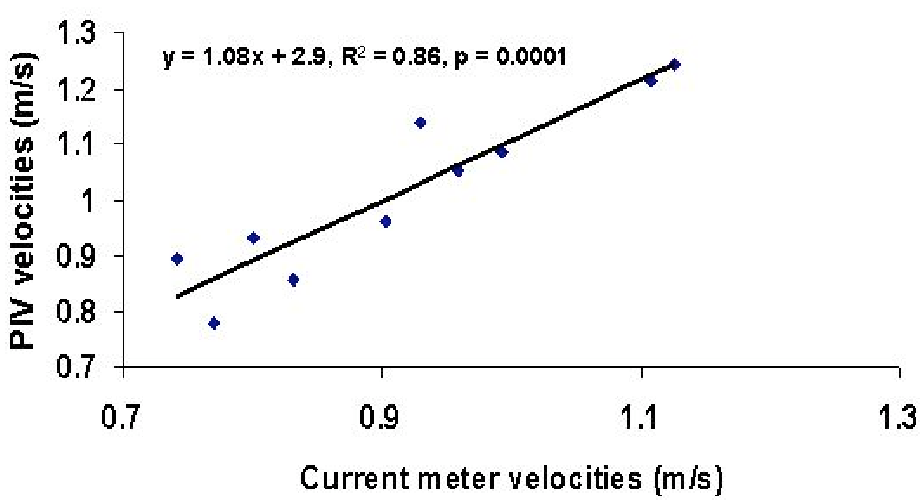

Figure 7. Current meter vs. filtered PIV measurements <15 m.

5 DISCUSSION

The results demonstrate that it is possible to obtain good PIV results even when field conditions are not ideal. When dealing with rivers that are fairly clear and shallow, effective removal of the bed effect is necessary to obtain accurate results. Additionally, the bank from which the images were recorded was not very high (~1.5 - 2 meters) and therefore distortion due to distance and the oblique recording angle was considerable. The oblique angle at which the videos were acquired resulted in distal interrogation areas covering a greater real surface area than proximal interrogation areas. These less than ideal conditions explain why additional processing was needed to obtain results comparable to those achieved on the River Wharfe in the UK [11]. The River Wharfe was very narrow (~ 8 m wide) with high banks and opaque water through which the riverbed was undetectable.

Despite problems encountered with visible riverbeds and surface water flares, there is a great potential for the use of this technique for long sections of river. Obtaining video records for one site using a single camera position required less than an hour of fieldwork. This included setting up the equipment, acquiring digital records of the water surface and taking control points, to finally dismantling the equipment. One field of view was filmed for 2-3 minutes and covered an area that would require a minimum of 15-20 points taken manually with a current meter in a grid of points separated along the transect by 2 m and by 5 m between transects. By interpolating the PIV velocities points in ArcView, we obtained a map of the surface water velocities. While it is equally possible to create a velocity distribution map with current meter-measured points, the input grid is considerably less dense than those possible with PIV measurements. With an interrogation area of 60 x 60 pixels and an overlap of 40 pixels, 216 surface velocity points were extracted from a single video clip. Additionally, the fieldwork required to obtain a sparser current meter velocity grid is both labour-intensive and time consuming.

6 CONCLUSIONS

This PIV technique shows promising results for application to longer river reaches. The technique requires a minimal amount of time in the field and yields a map of the surface water velocities suitable for habitat studies. Many rivers such as the Ste-Marguerite River, are clear and shallow with visible river beds that would necessitate the removal of this signal from the velocity calculations. Isolating and reprojecting velocities into the primary flow axis successfully removed flares at the water surface and made the velocities comparable to the current meter velocities. Future work will be done to test the PIV application on longer stretches of river and over multiple river morphologies. This will enable the rapid characterization of available fish habitat along riverscape scale river reaches.

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