# A Surface PIV Approach for the Remote Monitoring of Mean and Turbulent Flow Properties in an Open Channel

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## Introduction

The United States Geological Survey (USGS) operates ~7,000 stream gaging stations across the nation where a principal measurement is volumetric flow rate.

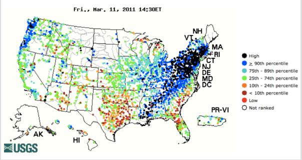

**Figure 1. USGS Stream Gauging Stations**

**Volumetric Flow Rate: $Q = VA$**
where V is the depth-averaged velocity and A is the river cross-sectional area.

The single-point measurement technique used by the USGS is inefficient and can be in error by as much as 70% during flood conditions.

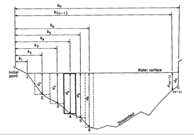

**Figure 2. Volumetric Flow Rate Measurement[1]**

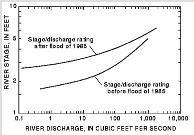

**Figure 3. Effect of Flooding on Rating Curve[2]**

## Objective

**Objective: Develop a methodology to remotely, continuously, and efficiently monitor fluid flow rate through measurements of the water surface and near-surface patterns.**

Hypothesis: In shallow flows, shear stress at the bed causes intermittent ejection of fluid away from the bed. Upwelled water interacts with and spreads radially along the water surface creating turbulent surface features which contain information about the underlying flow. Analysis of these features leads to determination of volumetric flow rate.

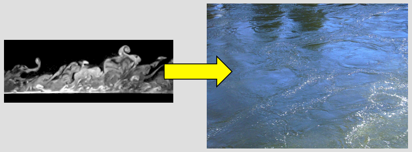

**Figure 4. Bed Shear Stress Leads to Turbulent Surface Features**

## Experimental Set-Up

To understand the correlation between the surface flow and the underlying bulk fluid flow, surface particle image velocimetry measurements (SPIV) were carried out in a wide open channel to characterize the surface fluid flow. Acoustic Doppler Velocimetry (ADV) measurements were also made to characterize the bulk fluid flow.

## Experimental Set-Up

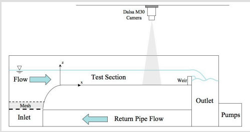

**Figure 5. Experimental Set-Up**

- Flow Depth: h = 15.5 cm
- Channel Width: 2 m
- 1M30P DALSA Camera
- Camera Lens: 20 mm, f/2.8
- FOV: 1.5 m X 1.5 m
- Pixel Resolution : 0.15 cm/pixel
- Sub-window : 64 x 32 pixels
- 1500 image quadruples
- Sampling Frequency: 1 Hz
- Eight 500 Watt Halogen Lamps
- Pliolite VTAC-L Particles

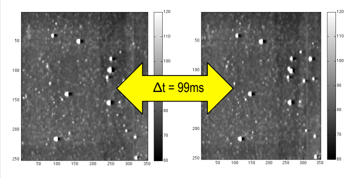

**Figure 6. Sample PIV Image Pair**

## Results – Mean Surface Velocity

Mean streamwise velocity field and profile reveal a weak velocity gradient across the channel. There is also evidence of a weak (5% of mean flow) cellular secondary flow which is characterized by alternating regions of upflow and downflow (as indicated by the red and black arrows in fig. 7).

$$0.85\,V_{surface} = V_{bulk\ average}$$

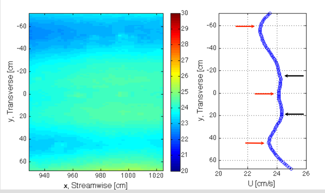

**Figure 7. Mean Streamwise Velocity Field & Profile, <U> [cm/s]**

The mean transverse velocity is an order of magnitude smaller than the mean streamwise velocity and is fairly constant across the wide channel.

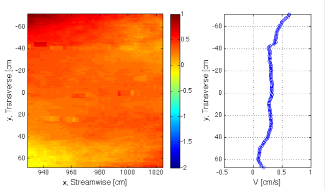

**Figure 8. Mean Transverse Velocity Field & Profile, <V> [cm/s]**

## Results – RMS Velocities

Turbulent Fluctuation : $u_i' \equiv U_i - \langle U_i \rangle$, where $U_i$ is the instantaneous velocity and $\langle U_i \rangle$ is the ensemble averaged velocity.

Evidence of the secondary flow is much more pronounced in the streamwise rms velocity than in transverse rms velocity. Regions of upflow appear as local maximums (indicated with red arrows) and regions of downflow appear as local minimums (black arrows).

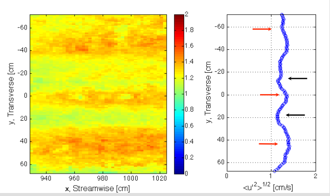

**Figure 9. Streamwise RMS Velocity Field & Profile, $\langle u'^2\rangle^{1/2}$ [cm/s]**

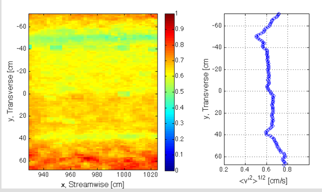

**Figure 10. Transverse RMS Velocity Field & Profile, $\langle v'^2\rangle^{1/2}$ [cm/s]**

## Results – Reynolds Stresses

$$\text{Reynolds Stresses} \equiv \langle u_i' u_j' \rangle$$

The Reynolds Stress represents the covariance of the streamwise and transverse velocity fluctuations. When the quantity is positive it indicates that both the streamwise and transverse fluctuations are acting in their respective positive directions. A negative sign indicates that one of the fluctuations is acting in its negative direction and the other is acting in its positive direction. These results give an indication of the direction of secondary flow rotation.

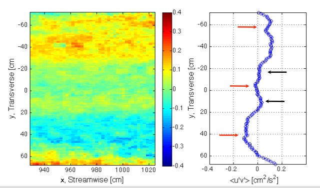

**Figure 11. Reynolds Stress Field & Profile, $\langle u'v' \rangle$ [cm$^2$/s$^2$]**

## Results – Integral Length Scale & Spectra

The surface integral length scale was calculated by integrating the autocorrelation function of multiple transverse profiles of turbulent velocity.

$$L_{ij,k} \equiv \int_0^L a_{ij,k}(r)\,dr \qquad \text{where, } a_{ij,k}(r) = \frac{\overline{u'_i\left(x_c - \frac{1}{2}r_k\right)u'_j\left(x_c + \frac{1}{2}r_k\right)}}{\left[\overline{u'_i\left(x_c - \frac{1}{2}r_k\right)^2}\;\overline{u'_j\left(x_c + \frac{1}{2}r_k\right)^2}\right]^{1/2}}$$

**The surface length scales are predictably related to the flow depth, *h*.**

$$L_{11,1} \approx 16.1\ \text{cm} \sim h$$

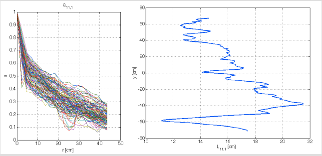

**Figure 12. Streamwise Autocorrelation Function and Integral Length Scale**

$$L_{22,1} \approx 4.6\ \text{cm} = 0.3h$$

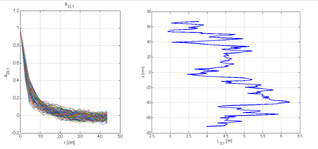

**Figure 13. Transverse Autocorrelation Function and Integral Length Scale**

$$E_{11}(\kappa_2) = \frac{2}{\pi}\int_0^\infty R_{11}(e_1 r_2)\cos(\kappa_1 r_2)\,dr_2$$

Normalized longitudinal spatial spectra exhibit a slight bump at the wave number corresponding to the flow depth.

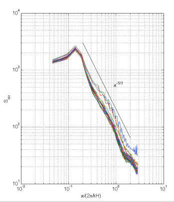

**Figure 14. Normalized Longitudinal Spatial Spectra**

## Volumetric Discharge Estimate

Using surface-bulk correlations, $V_{avg} \cong 0.85\,V_{surf}$ and $L_{22,1} \cong 0.3H$,

**Surface PIV Results: $Q = (V_{avg})bH \cong 0.044\ m^3/s$**

**Submerged Weir Theory : $Q = C_s B g^{1/2}(H_u)^{3/2} = 0.049 \pm 0.006\ m^3/s$**

## Future Work

Future experiments will include variations in Reynolds number, aspect ratio, bed roughness and channel cross-sectional geometry. Proof of concept experiments will be carried out in Fall Creek and Six Mile Creek.

[1] Rantz et al., 1982, USGS Water-Supply Pap. 2175.
[2] Mason & Weiger, 1995, USGS Fact Sheet FS-209-95.