

## **Laboratory and Field Application of River Depth Estimation Techniques Using Remotely Sensed Data: Annual Report Year 1**

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### **LONG-TERM GOALS**

Our long term goal in this and related projects is to maximize the amount of information regarding river flow and morphology that can be deduced from remotely sensed information. In this specific project, our goal is to test and improve the river bathymetry prediction methods developed in previous ONR-funded work. This goal involves further development on computational methods as well as exploration and refinement of methods for remotely measuring water-surface elevations and water-surface velocities. In previous work, we have been able to demonstrate that inversion of the momentum equations and morphodynamics modeling can be used to detect errors and fill gaps in various remotely sensed river bathymetry data sets (i.e., such as those measured using bathymetric LiDAR and various optical correlation techniques using multi- and hyperspectral scanning, as reported in Wright and Brock (2002), Kinzel et al., (2007), Legleiter and Roberts (2005), and Legleiter et al., (2004)). In the current project, we are looking at this problem in a more expansive sense by testing measurement techniques and computational approaches that can be used in the absence of any bathymetric estimate, as would typically be the case in rivers with high suspended sediment loads and/or deep depths, which limit optical techniques. Eventually, we envision that these two different techniques can be rejoined in a manner that is accurate, efficient and capable of providing meaningful error estimates for predicted morphology.

### **OBJECTIVES**

The specific objectives for the first year of this two-year effort were to (1) modify our existing inversion code to include higher-order effects neglected in our original development (Nelson, 2012), and (2) to develop and test methods for measuring water-surface elevation and water-surface velocities in the laboratory and, if possible, at field sites. As noted in our original proposal, we expected to investigate two methods for water-surface elevation measurements, one for smaller scale systems (laser-scanning) and one for larger systems (the AirSWOT methodology, see Rodriguez, 2010). For water-surface velocity measurements we planned to use the infrared videography methodology developed by others (e.g., Dugan and Piotrowski, 2003; Dugan et al, 2013; Kinzel et al., 2011). The first objective was relatively straight-forward, but the second required procuring laser scanning and infrared videography equipment and developing our capabilities in this area. Thus, most of our efforts

in this first year were directed at building and testing an infrared videography system and testing software for deriving water-surface velocities from that system. Our first-year work also included a smaller effort aimed at testing laser-scanning as a method for measuring water-surface elevation, and a relatively minor programming element aimed at adding higher-order elements to the inversion technique developed under our last ONR research effort.

## APPROACH

In our last round of ONR research effort, we developed a simple method for estimating depth based on water-surface elevation and water-surface (or vertically averaged) velocity. Instead of using a computationally-intensive inversion that solves for depth based on a full partial differential equation or uses a data assimilation technique involving many flow solutions, the equations expressing conservation of mass and momentum were simplified based on a few reasonable assumptions to give expressions that directly predict local flow depth as a function of water-surface elevation and vertically averaged velocity. For example, from the streamwise component of the equation expressing conservation of momentum for river flow, if we assume the flow is incompressible and quasi-steady, has no lateral stresses, and that a simple drag coefficient closure is suitable, we can directly obtain an equation relating local depths to local hydraulic variables, as follows:

$$h = \frac{-C_d \sqrt{\langle u \rangle^2 + \langle v \rangle^2} \langle u \rangle}{\left[ \frac{g}{1-N} \frac{\partial E}{\partial s} + \frac{\langle u \rangle}{1-N} \frac{\partial \langle u \rangle}{\partial s} + \langle v \rangle \frac{\partial \langle u \rangle}{\partial n} - \frac{\langle u \rangle \langle v \rangle}{(1-N)R} \right]} \quad 1$$

where  $N$  is a simple metric coefficient,  $R$  is the centerline radius of curvature of a channel-fitted centerline,  $g$  is gravity,  $C_d$  is a drag coefficient,  $\langle u \rangle$  and  $\langle v \rangle$  are vertically averaged velocity components in the streamwise and cross-stream directions, and  $s$  and  $n$  are coordinates locally oriented in the streamwise and cross-stream directions, respectively.

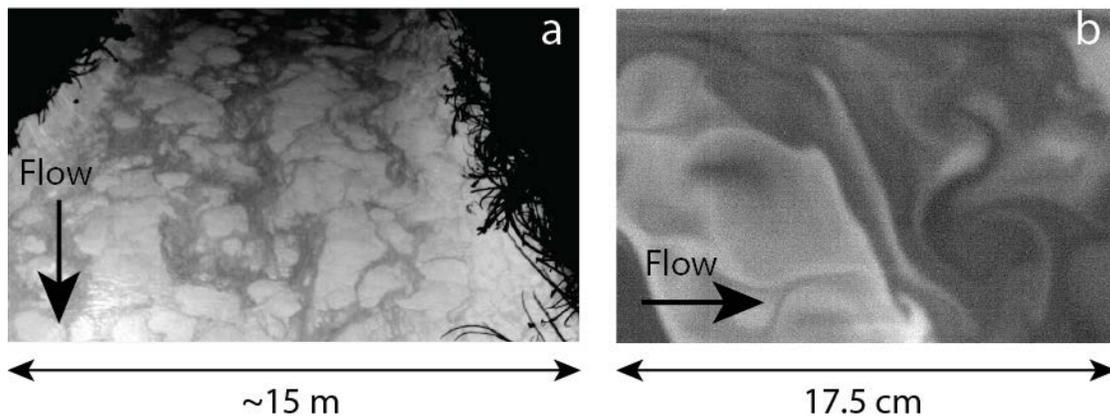
To test the expressions and investigate potential errors, we initially applied them to data sets developed from existing river models. Measured bathymetry was used to compute flows of a certain discharge in river channels using open-source, public domain model FaSTMECH (Nelson and McDonald, 1996; Nelson, Bennett and Wiele, 2003; McDonald et al, 2006) available in the International River Interface Cooperative (iRIC; [www.i-ric.org](http://www.i-ric.org)) river modeling package developed by our group and others. The predicted water-surface elevations and vertically averaged velocities were extracted from the model results and the depth was predicted from that information using the formulation above. While this is clearly circular, it allows us to start with data sets that are constrained to satisfy conservation of mass and momentum and, as discussed in one of our publications (Nelson et al, 2012), it provides some good physical guidance on issues with the approach and the effect of noise in the driving data.

We developed results of this process for two very different river reaches: the Trinity River in California, which is a relatively steep, shallow, coarse-bedded channel, and the Kootenai River in Idaho, which is a relatively flat, deep, sand-bedded reach. For each river, the inversion technique was applied directly to compare the computed and measured depths. The impacts of normally distributed noise in the input data sets (water-surface elevation and velocity) was also explored. Finally, the

impact of using surface velocity instead of vertically averaged velocity in the inversion method was investigated. These results are presented in Nelson et al. (2012).

As part of that earlier investigation, we were able to show that some terms neglected in the development of equation (1) were actually important in certain areas (notably lateral stresses near channel banks and other regions of strong lateral shear). Thus, as part of our first year effort on the current project, we developed a method that brings these neglected terms in iteratively. Thus, we now solve Equation 1, then use the estimated depths (and known water's edge data) to bring in the neglected terms in a simple manner.

The next step in this development was to get good enough laboratory and field data to test the approach. Most of our effort in this first year was spent on this. We believed from previous work that we could get water-surface elevations using laser scanners for small scale field sites and interferometric radar techniques (AirSWOT) for larger ones, but we were much less certain of our ability to get water-surface velocities. We investigated a few possibilities and decided that surface velocity measured using infrared videography (Dugan and Piotrowski, 2003; Dugan et al, 2013)) looked promising for remote collection of the velocity field. The basic idea is as follows. Flowing water has small temperature variations across the water surface that are coherent over timescales of seconds to minutes. Two examples are shown in Figure 1. These structures advect downstream at approximately the surface velocity of the flow and can be imaged with an infrared (IR) camera. Our goal is to create an image sequence (a movie) of these temperature variations and use a motion tracking algorithm to estimate the water-surface velocity field based on the change in the position of thermal structures between frames of the image sequence.



**Figure 1. Infrared images of water surfaces. a) an irrigation canal and b) a laboratory flume. Brighter areas are warmer than darker areas by  $< 1^\circ \text{C}$ .**

The basic concept behind a variety of image tracking algorithms is that the difference in the position of objects in two successive two frames of a movie is a displacement field. This concept is represented mathematically by the Displaced Frame Difference (DFD) equation:

$$I(x, y, t + \Delta t) - I(x, y, t) = v(x, y) \Delta t \quad 2$$

Where  $I$  is the matrix of image intensity at the pixel locations  $(x, y)$  at time  $t$ ,  $\Delta t$  is the time elapsed between successive frames, and  $\mathbf{v}(x, y) = dI(x, y, t)/dt$  is the vector velocity field representing the motion of objects in the image. We explored two approaches to finding the 2-dimensional velocity  $\mathbf{v}(x, y)$ , particle image velocimetry (PIV) and optical flow algorithms.

PIV is a technique for imaging fluid flows seeded with small particles that move at approximately the same velocity as the fluid flow. The flow is illuminated (typically with a laser) and a series of images is recorded. The velocity field is estimated by finding the displacement that maximizes the correlation between two successive frames of the images sequence. Typically, this accomplished by dividing the images into  $m \times n$  pixel sub-regions and finding a spatially averaged velocity for each sub-region. See *Raffel et al.* [2007] for a detailed discussion of PIV techniques. We found that PIV does not extract uniformly accurate velocity fields from the IR image sequences because of the variations in flow structure size.

Optical flow describes a broad class of algorithms that originate in computer vision research for tracking the motion of objects. Optical flow algorithms use minimization schemes to find the velocity field that minimizes the difference between two frames on a pixel-by-pixel basis. *Heitz et al.* [2010] recently reviewed optical flow algorithms designed specifically for estimating fluid flows. *Corpetti et al.* [2006] and *Dérian et al.* [2012] describe the specific implementations that we have applied to our image sequences. The DenseMotion implementation described by *Corpetti et al.* [2006] is available as a compiled Linux executable from <http://fluid.irisa.fr/publis/Deliverable2.4.tar.gz>. The implementation of the wavelet technique described by *Dérian et al.* [2012] is not publically available, but Pierre Dérian (currently at California State, Chico) has been collaborating with us and running some analysis. We expect that his software will become available at some point in the future and he has expressed interest in further collaboration.

The camera we used is a FLIR SC 8300 HD. The camera has an indium antimonide (InSb) sensor that detects mid-range IR light in the 3-5 micron ( $\mu\text{m}$ ) band. The sensor size is 1280 x 720 pixels. Temperature differences of 25 milli-Kelvins (0.025 K) result in a signal-to-noise ratio of 1 on the camera sensor. The minimum resolvable temperature difference is few times this number (on the order of 0.1 °C).

## WORK COMPLETED

Based on research efforts over the first 9 months of the first year of our ONR grant, the following tasks are complete:

- (1) We developed a computational method for including higher-order terms in the simple inversion method for estimating bathymetry.
- (2) We tested and confirmed that laser-scanners could potentially provide water-surface elevation data at the required density and accuracy for depth computation based on our inversion method.
- (3) We purchased an infrared camera using ONR and USGS funding and developed a system for using it in the laboratory and field to collect infrared videography for measuring water-surface velocity.

- (4) We carried out several laboratory experiments using the infrared camera to measure water-surface velocities
- (5) We tested several PIV methods and two optical motion methods for computing surface velocities from infrared videography.
- (6) We carried out three field experiments to measure water-surface velocity, two on local canals (Croke Canal and Church Ranch Canal) and a third on the Platte River near Confluence Park in Denver.

## RESULTS

In this section, we concentrate on the results of the water-surface velocity measurement work. One of the first things we learned from our measurement program was that, although PIV could provide velocity estimates from the infrared imagery, it was difficult to get uniform measurement coverage. This was because of the importance of structure size to the choice of an optimum PIV interrogation window. Thus, a PIV interrogation window that works for certain structure sizes fails for much smaller ones, so for different areas of the same image, there is no single window that works well. This means that it is difficult to get a complete coverage field of accurate velocity estimates unless all the observed structures are similar in size and the interrogation window can be appropriately tuned. We these lessons learned, we turned to more general optical flow motion methods, as discussed here.

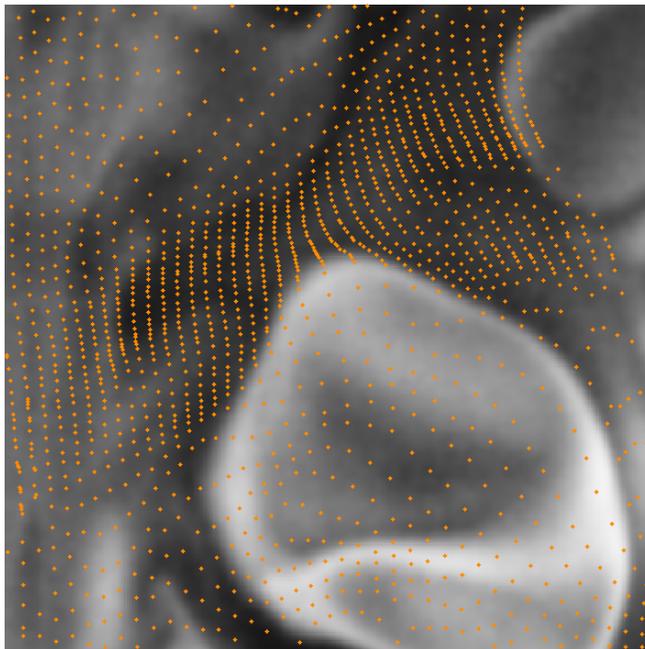
We recorded a series of image sequences of the flow in the small flume at the U.S. Geological Survey Geomorphology and Sediment Transport Laboratory (GSTL). The IR camera was mounted on a rack ~1m above the surface of the flow and oriented so that the image plane was approximately parallel to the surface of the water. We assumed that the image plane was exactly parallel to the water surface and that there is no distortion across the view so the scale (in pixels per cm) is uniform across the image.

In the laboratory, where water temperatures tend to be very uniform and viscous heating is very low, we obtained the best results using a combination of ice and aquarium heaters to “seed” the flow with temperature gradients. We floated a 10-pound block of ice (in a bag) in the flume upstream of the camera. Immediately downstream of the ice (and upstream of the camera), we attached two 200 watt and two 300 watt aquarium heaters to the side of the flume and placed a ~15 cm tall Plexiglas block on the bottom of the flume to increase vertical motion in the fluid. One image from the sequences is reproduced in Figure 1b. A ruler placed on the side of the flume where it was visible in the (uncropped) images provided scale control.

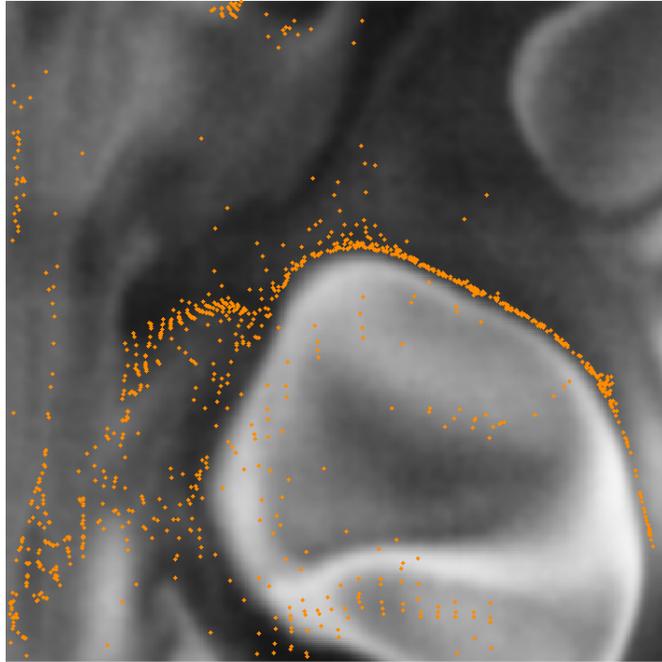
The image sequence was recorded at a resolution of  $384 \times 510$  pixels at 75 frames per second (fps). A minimal number of frames (~2) were dropped. The image sequence was cropped to  $320 \times 320$  pixels (to reduce processing time) and filtered both spatially and temporally to reduce noise. We also enhanced the contrast with an image processing application.

In general, the wavelet algorithm described by *Dérian et al.* [2012] gives a better estimate of the velocity field than that of *Corpetti et al.* [2006]. This can be seen in Figures 2 and 3, which show fields of virtual “particles” moving according to the estimated velocity fields. In the wavelet estimate (Figure 2), “particles” follow the advection of the thermal structure more faithfully than in the DenseMotion estimate (Figure 3). This is easier to see on the videos on our ONR QUAD than it is using a still image, as shown here. The velocity distribution estimated by the wavelet algorithm is

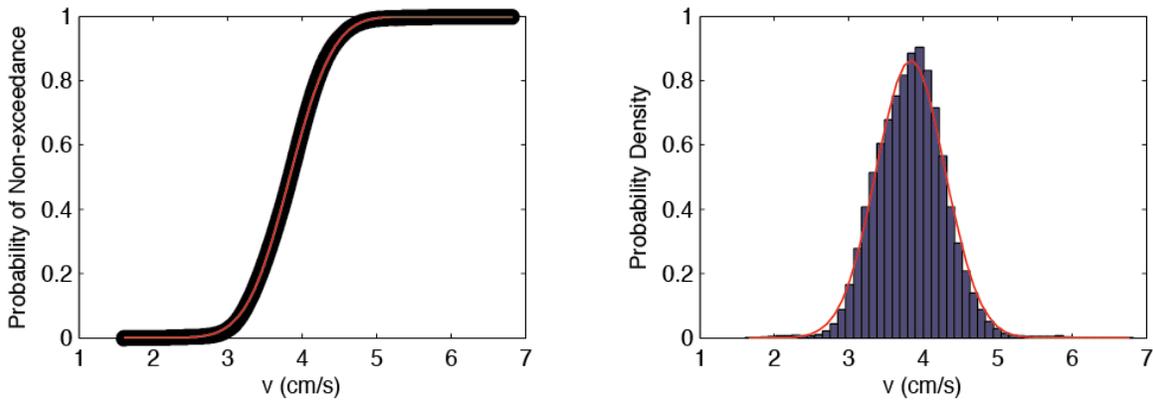
shown in Figure 4. The DenseMotion estimate is shown in Figure 5. No independent detailed measurement of the flow velocity exists, but the visual correspondence between the motion of thermal structures and the motion of the “particles” in Figure 2 suggests that the wavelet estimate is accurate. Both the wavelet and DenseMotion algorithms have difficulty estimating velocity in areas of low image contrast, but the problem is much worse in the DenseMotion estimate, which results in clustering of the virtual particles (Figure 3) at high contrast boundaries and an overall lower estimate of the mean velocity.



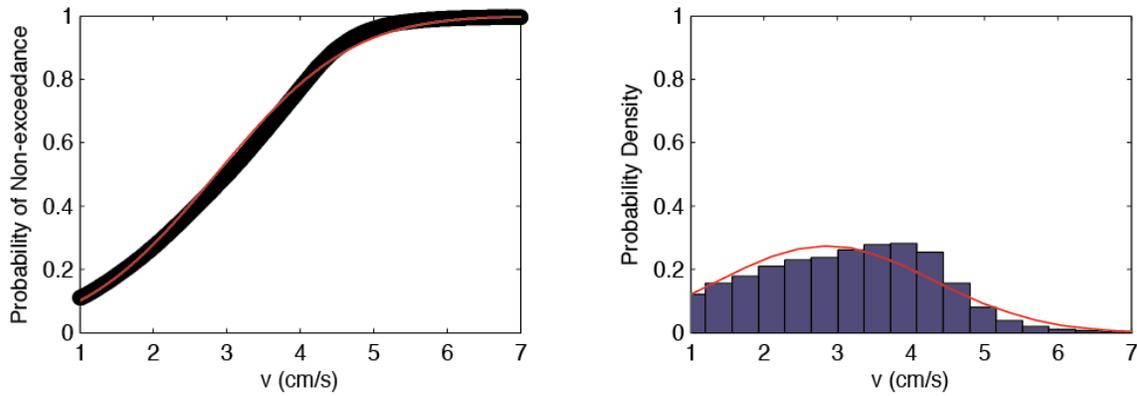
***Figure 2. Visualization of velocity field estimated with the wavelet algorithm using particles advected by the predicted velocity field. See QUAD for video animation.***



**Figure 3. Visualization of velocity field estimated by DenseMotion using particles advected by velocity field estimate. See QUAD for video animation.**

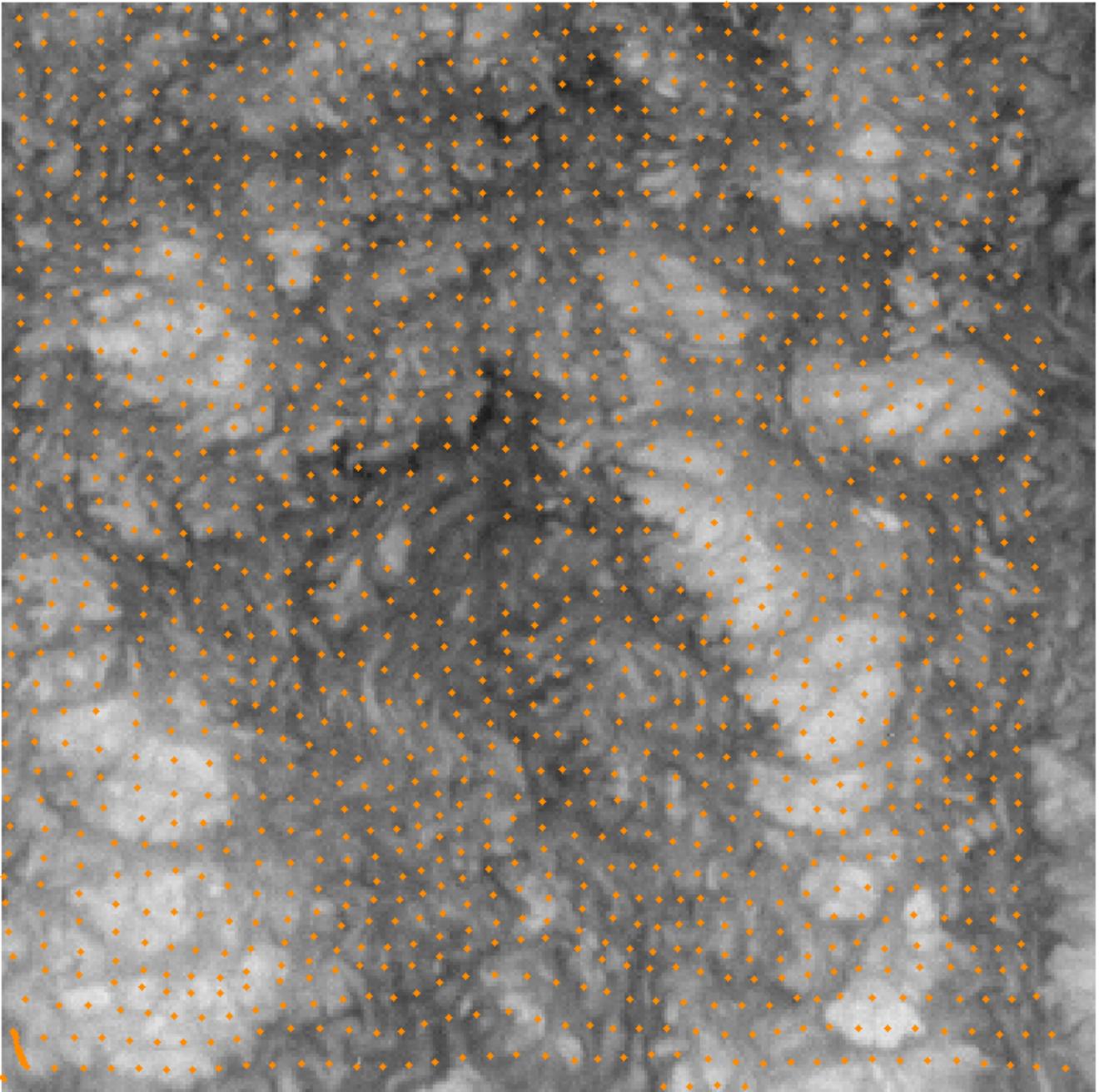


**Figure 4. Velocity distribution estimated by the wavelet algorithm. Cumulative distribution function (CDF) is on the left, probability density function (PDF) is on the right. The red lines are the best fitting Gaussian distribution.**



***Figure 5. Velocity distribution estimated by DenseMotion. Cumulative distribution function (CDF) is on the left, probability density function (PDF) is on the right. The red lines are the best fitting Gaussian distribution.***

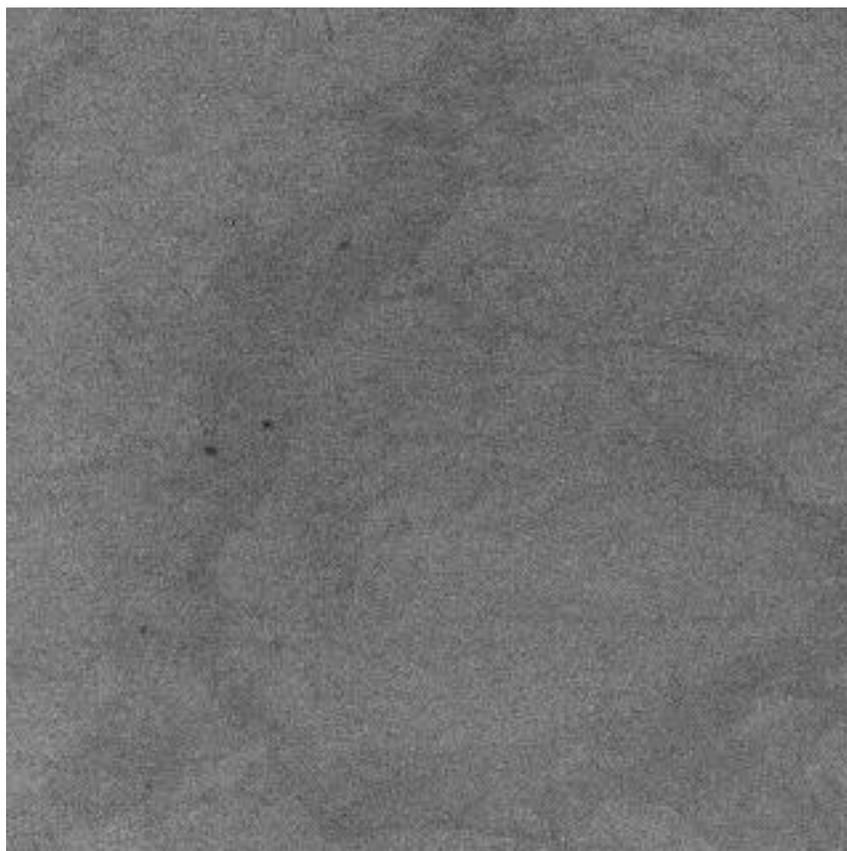
In addition to many similar laboratory sequences, we also deployed the camera system in three field settings. Figure 6 shows an image from a sequence taken from a bridge over the South Platte River at Confluence Park in Denver in the early morning of July 31, 2013. The visualization of the wavelet velocity field estimate using advected particles is shown in Figure 7 (a video of this interesting flow field is also shown in our ONR QUAD sheet).



***Figure 6. South Platte River recorded from a pedestrian bridge in Confluence Park, Denver with a visualization of the wavelet estimate of the flow field.***

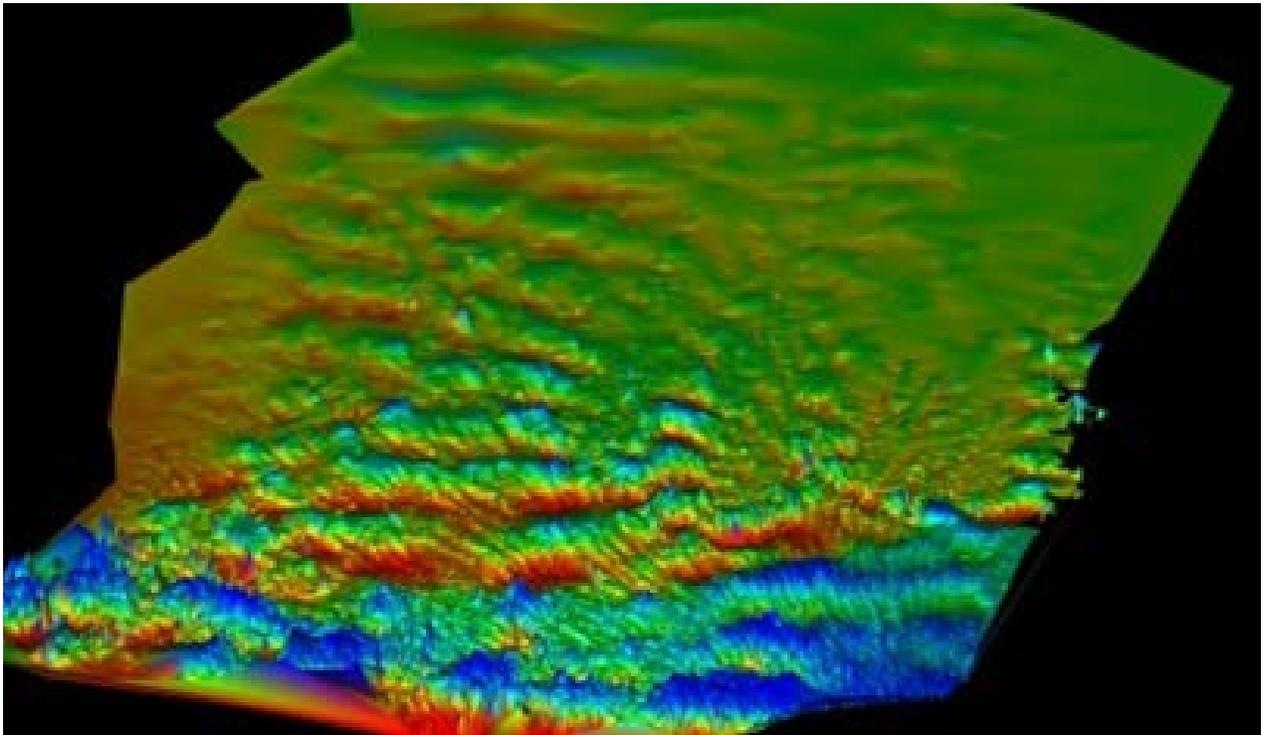
We encountered a variety of issues during this work. First, infrared radiation reflected off of the water surface is a significant problem. On sunny days, the reflection of the sky off the water surface makes the thermal structure much more difficult to image. This is less of a problem on overcast days. The irrigation canal image shown in Figure 1 was shot at mid-day on an overcast day in February. The image sequence shown in Figure 7 and discussed in the next section was recorded in the mid-afternoon on an overcast summer day (8/7/13).

IR glare can be a problem even at night. Glare is most evident if there is vegetation along the banks and the channel is narrow. We believe this is due to infrared radiation from the vegetation. Because light reflected off of non-metallic reflective surfaces becomes polarized, we believe some of the issue with reflected radiation can be mitigated, but we have not yet tried. Visual light photographers use polarizing filters to reduce glare. It seems reasonable to expect that an IR polarizing filter might be similarly useful. Infrared polarizers are available for a few thousand dollars.



***Figure 7. Irrigation canal recorded on the overcast afternoon of 8/7/13.***

In addition to exploring these techniques for measuring detailed surface velocities, some preliminary work on measuring field water-surface elevations with laser scanners was completed. This was done because, even though we had accurate methods for measuring detailed water-surface elevation in the lab, the techniques are not amenable to application over large field areas; using a laser scanner is potentially a good field method, although we were unable to find previous work where this method had been applied and tested with other measurements. We carried out several field data acquisitions and were able to show that the scanner can measure surface elevations very quickly over an entire reach, as shown in Figure 8.



*Figure 8. Laser scanner image of water-surface topography at the confluence of the Platte River and an irrigation canal. Comparisons to ground-based surveying suggests we can resolve the water surface to within 1-2mm, less with averaging.*

Finally, as part of the same effort to develop field techniques for measuring water-surface elevation, we spoke with researchers on the NASA AirSWOT program and were instrumental in planning a combined effort for data collection on the Sacramento River this Fall. AirSWOT surface-elevation data will be collected and USGS will work on collecting both truth data for comparison and bathymetry and velocity. We hope to include some component of infrared videography for water-surface velocities, but this is uncertain at this point.

## **IMPACT/APPLICATIONS**

The research work carried out under this project is also playing a significant role in USGS developments for practical applications of non-contact gauging. In addition, we have added the inversion model code to the iRIC modeling interface, so it will be freely available to the public in the next major release, expected May 2014.

## **RELATED PROJECTS**

We continue to tie this work to other research projects, including work on the Kootenai, Platte, and Russian Rivers. In addition, we are working closely with NASA and personnel at the USGS California Water Science Center on the application of the AirSWOT water-surface topography testing program on the Sacramento and hope to have access to those data sets sometime later this year or early next.

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