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Methodology Assessment for Large-Scale Particle Image Velocimetry

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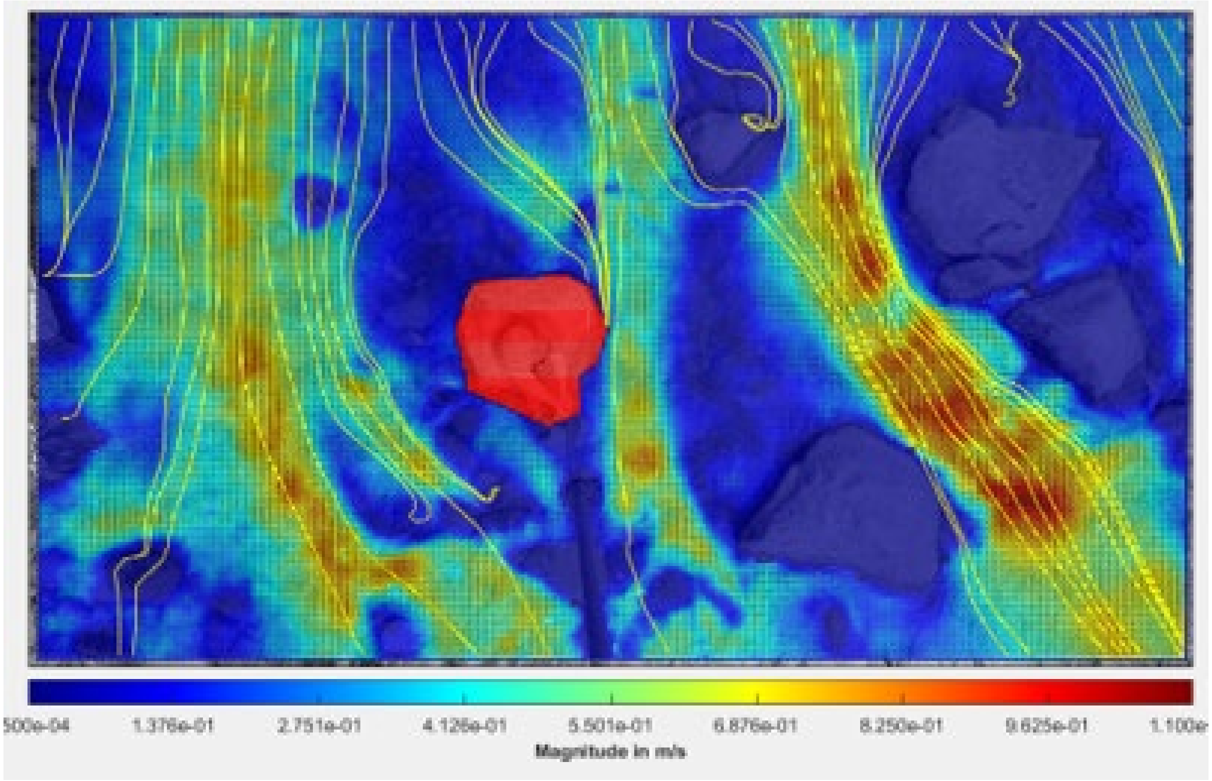

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14. ABSTRACT
Large-Scale Particle Image Velocimetry (LSPIV) is a technique utilized by Reclamation and other entities to obtain surface velocity measurements both in field and laboratory settings. Results from this study indicate that both field and laboratory flow measurements required the addition of seeding material, even under turbulent conditions. Effective seeding materials included high-contrast, easily dispersible particles such as wood shavings, polystyrene spheres, and dark-colored water beads, all of which minimized clumping and enhanced particle visibility. Camera settings of 30 frames per second were sufficient for measuring velocities below 3 ft/s. For higher velocities, 60 or 120 frames per second are sufficient, with the goal of having a particle move approximately 2 pixels per frame. For current laboratory and field applications, PIVLab was identified as the preferred processing software, as TRiVIA was limited by its requirement for aerial video input. Future work should include the evaluation of Reclamation's recently acquired LiDAR-compatible UAS system for LSPIV data collection, followed by a comparative assessment of available processing software.

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Disclaimer

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Cover Image – LSPIV data output from field testing. Image generated in PIVLab (Melissa Shinbein/Bureau of Reclamation).

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Executive Summary

Large-Scale Particle Image Velocimetry (LSPIV) is a technique utilized by Reclamation and other entities to obtain surface velocity measurements both in field and laboratory settings. This study aimed to address three key points:

1. What seeding material can be used to accurately represent the flow around objects of interest?
2. What data collection technique provides the most accurate results for laboratory and field use?
3. What are the best approaches to analyze collected data?

To assess these questions, both laboratory and field testing were conducted. Laboratory testing occurred in Reclamation's Hydraulics Laboratory. Field testing occurred at two river sites near Wenatchee, Washington. Between these locations, the following variables were tested:

1. Four seeding materials and no seeding.
2. Three camera frame rates.
3. Two types of cameras.
4. Two processing software packages.

Results from this study indicate that both field and laboratory flow measurements required the addition of seeding material, even under turbulent conditions. Effective seeding materials included high-contrast, easily dispersible particles such as wood shavings, polystyrene spheres, and dark-colored water beads, all of which minimized clumping and enhanced particle visibility. Camera settings of 30 frames per second (fps) were sufficient for measuring velocities at or below 3 ft/s; at velocities higher than 3 ft/s frame rates greater than 30 fps, higher frame rates tended to produce artificially elevated velocity estimates. For velocities above 3 ft/s, a minimum framerate of 60 fps is necessary for accurate velocity estimates, with the overall goal for planar LSPIV for a particle to move approximately 2 pixels between frames. For current laboratory and field applications, PIVLab was identified as the preferred processing software, as TRiVIA was limited by its requirement for aerial video input. Future work should include the evaluation of Reclamation's recently acquired LiDAR-compatible UAS system for LSPIV data collection, followed by a comparative assessment of available processing software.

1.0 Introduction

Large-Scale Particle Image Velocimetry (LSPIV) is a technique utilized by the Bureau of Reclamation (Reclamation) and other entities to obtain surface velocity measurements both in field and laboratory settings. LSPIV differs from other techniques used to collect velocities in that it uses images to track particle movement, often seeding material such as foam beads in the lab or a biodegradable option in the field, over time. As this method of acquiring velocities is non-intrusive, it can be used in areas of interest that would be harder to access or are too shallow for other velocity measurement techniques. Additionally, in a laboratory setting, LSPIV allows for simultaneous velocity vector mapping of the water surface as opposed to point velocity measurements. Currently, Reclamation's Hydraulics Laboratory uses LSPIV on physical hydraulic models and field studies that benefit from streamlined information about surface velocity data, such as habitat restoration and fish passage projects. However, there are issues with the LSPIV techniques currently being employed. Clumping of the seeding material and settings in the data collection process can skew velocity readings around key areas. This can result in less accurate information about the performance of fish passage and river restoration projects. Recently, new advances have been made in software processing packages including U.S. Geological Survey's (USGS) recently released TRiVIA. This project aims at testing LSPIV techniques from seeding material to data processing, ensuring that best practices are being utilized.

1.1. Previous Work

LSPIV has been used on many physical hydraulic models and field studies. To best demonstrate the gaps in this technique, two main projects are cited: Reclamation Science and Technology S&T project ID 1726 (Holste, et. al. 2019) and Hydraulics Laboratory report HL-2020-10 (Shinbein, 2020). These studies looked at the effects of boulder clusters in the Los Angeles River for fish resting and passage. While the velocity vector data from a physical model around boulder clusters could be observed for general trends, it was difficult to discern quantitatively reliable velocity values. Additionally, the significant clumping of seeding material around the boulder clusters resulted in some skewed velocity vectors at areas of recirculation, which are a key area of interest for fish passage. Results from PIVLab were taken into TecPlot to generate velocity maps of acceptable areas for fish resting zones, moderate resting zones, and not acceptable zones where velocities were too high for resting. While this was helpful to view, it was still difficult to discern what was happening between the boulders that comprised the boulder cluster.

For these laboratory projects, polystyrene beads were uniformly introduced into the physical model by using a leaf blower. The seeded water surface was recorded for a minimum of 10 seconds using a GoPro at 30 fps. The frames from the video were extracted using RIVeR and processed to generate velocity maps in PIVLab. In a more recent project, output from PIVLab was processed through TecPlot and then overlaid on an image of the physical model. This was significantly more useful in observing surface velocity trends relative to critical infrastructure proposed in the model versus prototype. However, while data presentation techniques have improved, the key problems of LSPIV still remain. Both studies used PIVLab as the primary software package, which has not been updated since 2017. Newer versions of PIVLab software are now available. Additionally, clumping of seeding material around areas of recirculation and due to static electricity between the particles can skew velocity readings in those areas. Refining LSPIV techniques will prove useful for future physical models and field data collection efforts.

1.2. Objectives

The research aimed to address three key points:

1. What seeding material can be used to accurately represent the flow around objects of interest? This project tested three different materials often used by Reclamation and similar entities.
2. What data collection technique provides the most accurate results for laboratory and field use? This project tested three different techniques for distributing seeding material at three different flow rates.
3. What are the best approaches to analyze collected data? This project investigated two different software packages.

To answer these questions, first a literature review was conducted. Second, both field and laboratory LSPIV site data were collected. This data was collected simultaneously with other velocity data collection techniques, including Acoustic Doppler Velocimetry (ADV) and Nixon meter velocity measurements. Finally, the data was processed using two different readily available software packages.

2.0 Literature Review

The literature review for this project focused on ascertaining best practices for LSPIV data collection and analysis. For this reason, data sources were varied, as LSPIV is a wildly used technique. The main results of the literature review for particle seeding were as follows:

1. In highly turbulent flow, seeding material was often omitted from data collection with success. Instead of seeding material, natural elements such as air bubbles, sunlight, and aerated flow within the footage were used (Fujita, 1998. Hauet, 2007/2008; Creutin, 2003).
2. Many used high color-contrast plastic beads or eco-foam of differing sizes and colors (Fujita, 1998; Sutarto, 2015; Braat, 2018; Leuven, 2019/2020).
3. Light floating debris, ice blocks, ground black pepper, and saw dust were also successfully used as more natural alternatives to the plastic beading (Muste, 2008/2014).

For a comprehensive list of all literature assessed during this review, please see Appendix C.

From these results, the laboratory and field test matrix were shaped to try a range of different seeding material, data collection tools, and processing software. Given the demonstrated success of others in using turbulent water without seeding material, each field site was tested both with and without seeding material to evaluate the necessity of seeding in typical environmental conditions. For laboratory testing, three seeding materials were selected based on the ease of recapturing the material or the ability of the material to break down naturally without capture in the laboratory. For both field and laboratory testing, different frame rates and processing software were utilized. A result of this study includes workflows generated for two different processing software products for future needs. These can be found in Appendices A and B.

3.0 Laboratory Testing

Laboratory testing was conducted at the Bureau of Reclamation's Hydraulics Laboratory in a physical hydraulic model of a river system. This model was selected due to the open flow channels. Additionally, this model contained rocks, which tested how the seeding material performed in recirculating areas and would be more similar to field applications.

3.1. Methods

In the lab, three different seeding materials were tested in the same physical hydraulic model. These materials were:

1. Polystyrene beads – these beads are the current seeding material used by the Hydraulics Laboratory for LSPIV.
2. Water beads – these are gel-like beads that expand and become buoyant when soaked in water. These beads come in a variety of different colors. For this test, all colors (red, green, and black) were combined in one bulk container.
3. Dyed ice cubes – ice cubes were dyed dark purple. The idea was that the ice cubes would melt and thus not require capture.

The seeding material was dispersed by a leaf blower, small pre-measured quantities simultaneously, and all at once further upstream in the model. As the leaf blower only worked for the polystyrene beads, this dispersion method was not compared. Seeding material was introduced where flow entered the model (at the bottom of the figures presented in section 3.2.1) for a minimum of 10 seconds, continuously.

All data was collected using a GoPro camera. However, the frames per second (fps) were changed during testing from 30 fps to 60 fps to ascertain if increasing the frame rate improved the data collection capabilities of the GoPro camera. Data were processed using RIVeR, PIVLab, and TRiVIA. Separate velocity data was collected using a Nixon Meter for comparison to LSPIV data. RIVeR takes the initial video data and pulls out each individual frame of the video for a given span of time. RIVeR was consistently used for all video datasets as it is the most efficient and easy-to-use software for this purpose.

PIVLab is software currently utilized by Reclamation for LSPIV processing needs. Previous data processing efforts were completed using a version of the software that was released in 2017. A newer version of PIVLab has been released as recently as 2024. The newest version of the software was used during this research project. During processing, a velocity vector map of the mean velocities throughout the duration of the video is produced. These are the maps used in the final figures as they provide the most coherent trends. The downside of PIVLab velocity vector mapping is the only units available for processing are in metric. To convert to English units, data must be exported to Microsoft Excel, converted to English units, and processed again in TecPlot. As this is a known process, it was omitted from the study to focus on software improvements.

The Toolbox for River Velocimetry using Images from Aircraft (TRiVIA) was released in 2023 as a processing interface created by the USGS for processing LSPIV software from unmanned aerial systems (UAS). At the time of this project, Reclamation did not possess a UAS capable of collecting LSPIV data. However, as this software showed promise in processing large LSPIV datasets, it was decided to test this software. As part of this study, workflows were created for both the newest version of PIVLab and TRiVIA. These can be found in Appendix A and B.

3.2. Results

3.2.1. Differing Material and Frame Rates

Polystyrene beads are the currently utilized seeding method in Reclamation's Hydraulics Laboratory. Issues with this seeding material include clumping due to static electricity produced by the beads in the leaf blower, difficulty in recollecting the beads, and the non-degradability of the plastic. While testing this material, 5-gallon containers that did not generate a charge were used. Notably, clumping was not as pronounced as previously seen in other models which was likely due to the supercritical flow regime in the tested physical model. As the seeding material moved from the entrance to the model to the exit (bottom to top of Figure 1), velocity data was generated for 30 and 60 fps. The 60 fps test was able to capture the side channels in the model better than the lower frame rate; however, resolution was lost further downstream. Compared to the velocities collected using the Nixon meter, the upstream and right side of the image agreed more with the 60 fps tests as those areas exceeded 3 ft/s (shown as red in the image). Downstream velocity measurements showed greater agreement with the 30 fps scenario. This is potentially due to the lower than 3 ft/s velocities seen in those sections of the model (Figure 1). Overall, modifications can be made to improve the dispersion and recollection techniques for the polystyrene beads.

Ice cubes proved to be an ineffective seeding material for laboratory flow visualization due to significant challenges in distribution and stability. They were initially selected because they would melt without generating the cleanup issues associated with polystyrene beads. However, the same property that made ice cubes appealing ultimately limited their utility. As ice cubes were dyed to increase contrast, a requirement for seeding material, they would immediately begin to melt. Thus, by the time the ice cubes were distributed in the model, it was difficult to distinguish discrete particles from the dye plumes created by melting. This issue not only reduced the number of trackable tracers but also degraded overall image clarity, complicating the software's ability to resolve coherent velocity vectors. Therefore, velocity maps generated from the ice cube tests are not reliable (Figure 2). Although the velocity maps generated at the 60 fps test scenario were consistent with Nixon meter measurements, the accuracy and clarity of the results were compromised by ice cube melting, non-uniform seeding dispersion, and dye leaching, which obscured the field of view. A potential improvement for ice cubes could include purchasing a separate ice maker to generate smaller, pre-dyed ice cubes. Until such modifications are implemented, however, ice cubes are not recommended as a primary seeding material for LSPIV applications.

Water beads, sometimes known by the brand name "Orbeez", had the same recollection and distribution problems as polystyrene beads. Once in the water column, water beads are naturally buoyant and due to the deformable and delicate consistency, they were difficult to recollect without breaking the beads. Additionally, water beads need to be presoaked in order to expand to the correct buoyancy. This means that distribution techniques that use electric components, such as leaf blowers, could not be used without risk of damaging the battery or internal electrical components. Significant deviations between 30 and 60 fps were caused by the concentration of darker color water beads (Figure 3). In the 30 fps scenario, much of the velocity flow data is missing from the upstream portion, bottom part of the frame, of the data. As darker water beads were used, velocity data becomes clearer at the 60 fps scenario. Additionally, in the portion of the model where velocities exceed 3 ft/s (shown as red in the velocity map), the 60 fps map has higher agreement with the Nixon meter velocity data. Therefore, only high-contrast color water beads should be used. Additionally, as less water beads are used than polystyrene beads, a higher frame rate is needed to correctly capture the velocity data and generate correct velocity field maps.

As other seeding options were not viable for immediate use without significant changes to every aspect of implementation, it is worth simply improving the re-collection techniques for the polystyrene beads. Modifications can include adding dryer sheets to remove the static charge from reused beads.

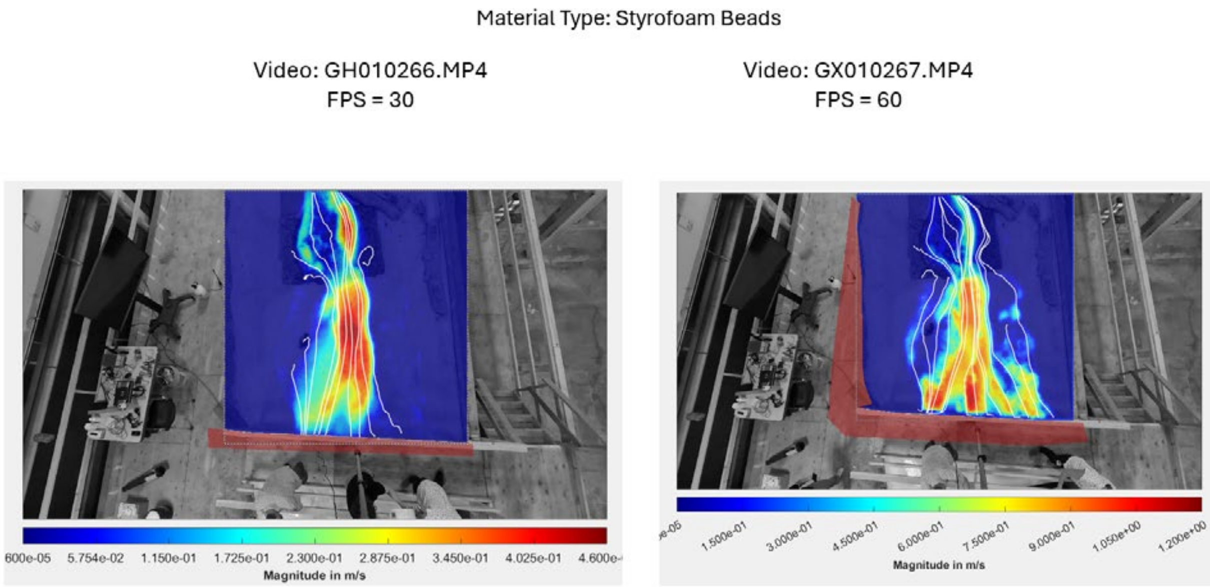

Figure 1. PIVLab outputs of the mean velocity vector mapping at 30 and 60 fps (right) using polystyrene beads. Flow moving from the bottom of the frame to the top. Note: red areas at the edge of the colored velocity maps are masked and excluded from processing.

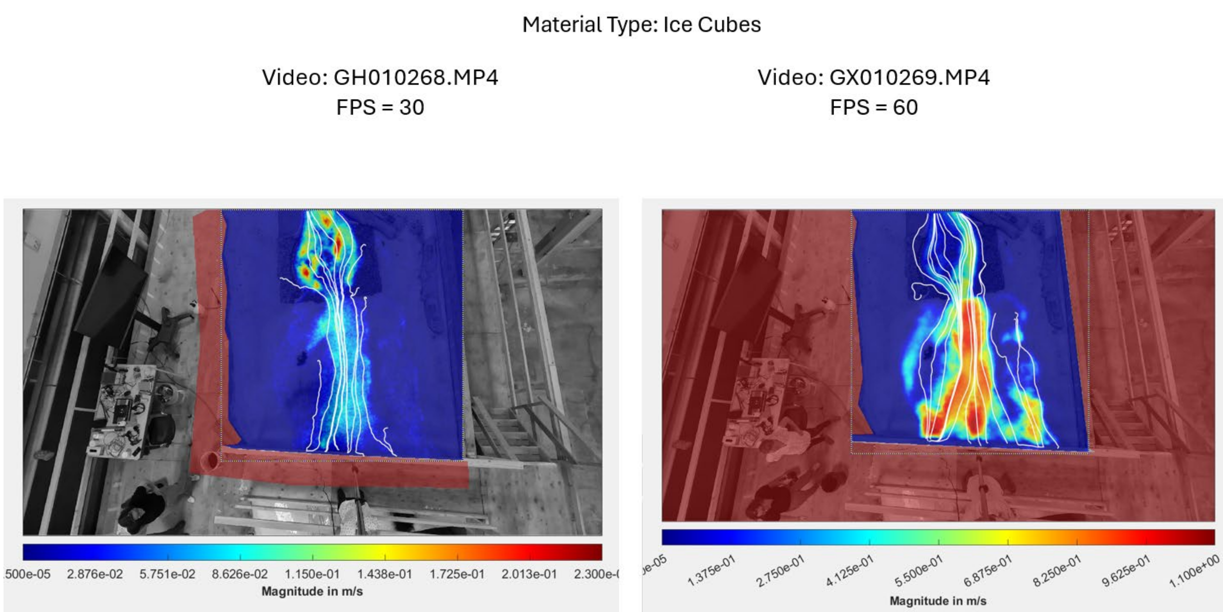

Figure 2. PIVLab outputs of the mean velocity vector mapping at 30 fps (left) and 60 fps (right) using dyed ice cubes. Flow moving from the bottom of the frame to the top. Note: red areas at the edge of the colored velocity maps are masked and excluded from processing.

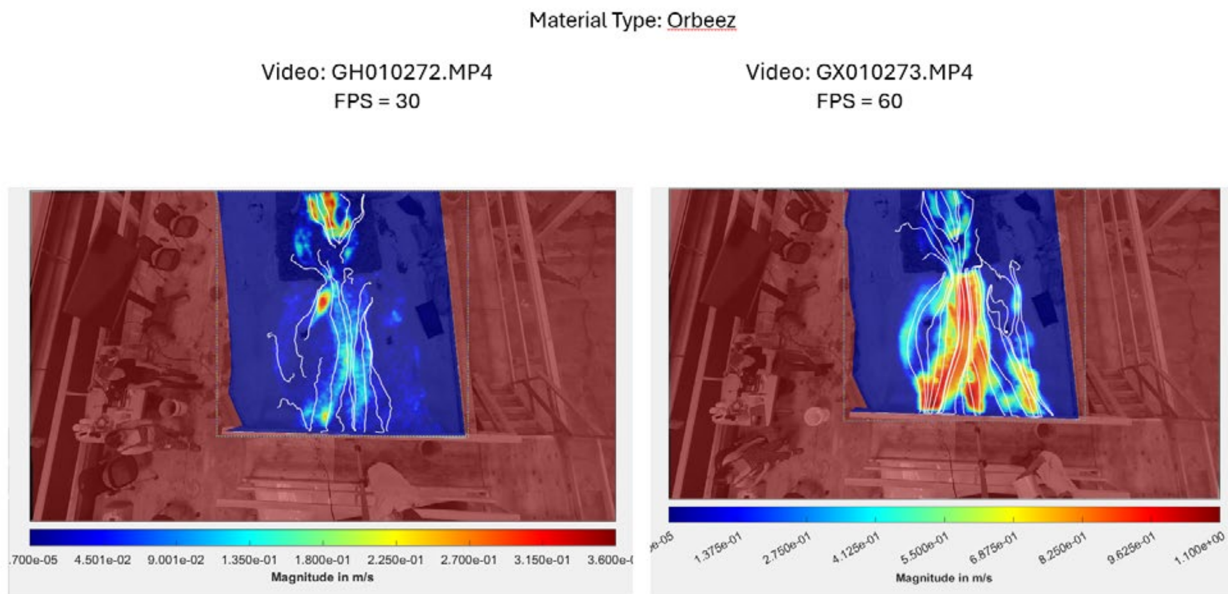

Figure 3. PIVLab outputs of the mean velocity vector mapping at 30 fps (left) and 60 fps (right) using water beads (Orbeez). Flow moving from the bottom of the frame to the top. Note: red areas at the edge of the colored velocity maps are masked and excluded from processing.

4.0 Field Testing

Field testing for LSPIV data collection techniques occurred at the Wenatchee and Entiat Rivers in central Washington. The Wenatchee River recently underwent modifications to the channel to include boulder clusters and large woody debris jams for fish passage and habitat.

4.1. Methods

As the field testing was on an open river with no way of re-collecting dispersed seeding material, environmentally friendly options were used. These materials included:

1. No seeding material – as the flow surrounding the boulder clusters was turbulent, it was decided to attempt to collect LSPIV data without any material added.
2. Wood shavings – cedar wood shavings were buoyant, easy to find in local stores, and easy to distribute. All figures presented use wood shavings as the seeding material.
3. Natural leafy material – similar to wood shavings, it was thought that leafy material would be easy to find and, as it would come from the banks of the river, would not pose an environmental risk. However, this material was extremely difficult to distribute and, as such, was not used for more than one trial.

The material was all dispersed by hand, upstream of the features of interest so as to not disrupt the flow around the features. Data collection used both GoPro cameras and government-issued iPads at 30, 60, and 120 fps. Additionally, several different field of views were trialed using an iPhone 15 Pro at the same location. This included introducing distortion via the zoom out feature to test distortion correction algorithms in RIVeR and PIVLab software packages.

As part of this process, two different software products were tested:

1. PIVLab – this was the software used within Reclamation's Hydraulics Laboratory at the start of this project. However, the version previously used was issued in 2016. As part of this study, the software was updated to the 2024 version to test the new features included in those updates.
2. TRiVIA – the Toolbox for River Velocimetry using Images from Aircraft was created by USGS to process LSPIV data from aircraft such as UAS.
3. LSPIV processing app available on iPad called "LSPIV" – this approach was considered however, it was not clear how this data would be protected in using the internet connected app. Therefore, it was decided not to use this software.

Similarly to the laboratory testing, the software RIVeR was used to extract frames from all videos. Additionally, separate velocity data was collected using an ADV (Flow-Tracker 2) to compare LSPIV data. While the ADV is used to collect velocities at approximately 60% of the water depth and LSPIV is velocity data at the surface, the data was used as a basis of comparison.

4.2. Results

4.2.1. Differing Frame Rates

Looking at the mean velocity field maps (Figure 4 and Figure 5):

- These images represent mean velocity vectors collected over the duration of the video. All videos were seeded with wood shavings and were tested at 120, 60, and 30 fps.
- Velocity trends are consistent for all tested frame rates. However, 60 fps skewed towards representing the velocities as higher when compared to 120 and 30 fps in the same area, particularly to the left and right of boulders where some turbulence would cause flow to naturally accelerate in that area.
- There are some variances in streamlines, partly due to the way they are specified manually in the software.
- Big flow features (e.g., boulders) are captured well in all three frame rates. Streamlines where flows are particularly low, such as downstream of boulders, show up best in 30 fps. Flow immediately downstream of rocks recirculated due to the boulder acting as a large obstruction in the flow field. At the higher frame rates, this recirculation created noise in the streamlines, represented as extra spiral lines.

Looking at the velocity scatterplots (Figure 4 and Figure 5):

- 120 fps had the highest frequency of single-point outliers, represented as individual points in the velocity scatterplot. This can be minimized by using PIVLab's velocity range selection tool, however differentiating true outliers from relevant data remains challenging.

- 60 fps had the widest range of velocities in the x-direction. This is represented as the darker red in the imagery and was originally thought to be human error in seed distribution. However, this trend was consistent in multiple tested scenarios.
- 30 fps had the tightest scatter in both the x- and y-directions.

These velocity histogram trends were consistent for all tested scenarios. Therefore, having an idea of the known range of velocities is key in selecting the frame rate. Velocities under 3 ft/s, the most common range for subcritical riverine environments where it is safe for wading and in the laboratory, should use 30 fps to provide the best results.

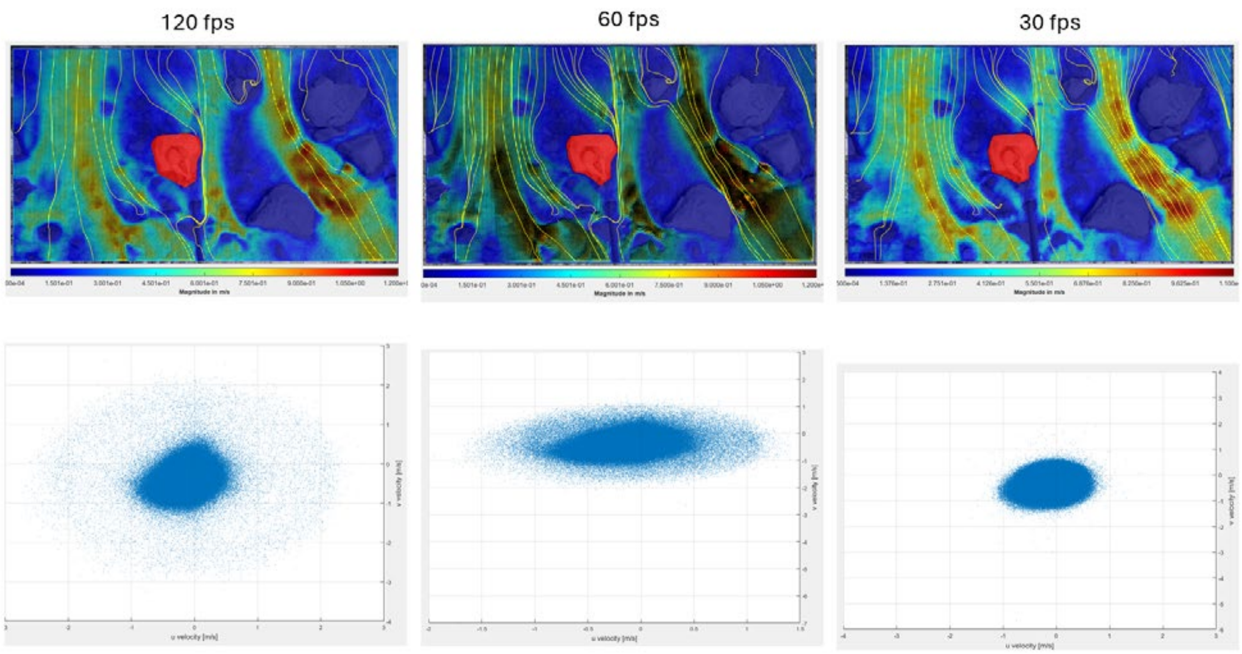

Figure 4. PIVLab outputs of the mean velocity vector mapping at 120 (left), 60 (center), and 30 fps (right) with velocity scatterplot. Video was collected using a GoPro HERO 10. Flow moving from the bottom of the frame to the top. Note: red area in the center of the image is masked, or excluded from processing, and represents where the camera was mounted in the frame.

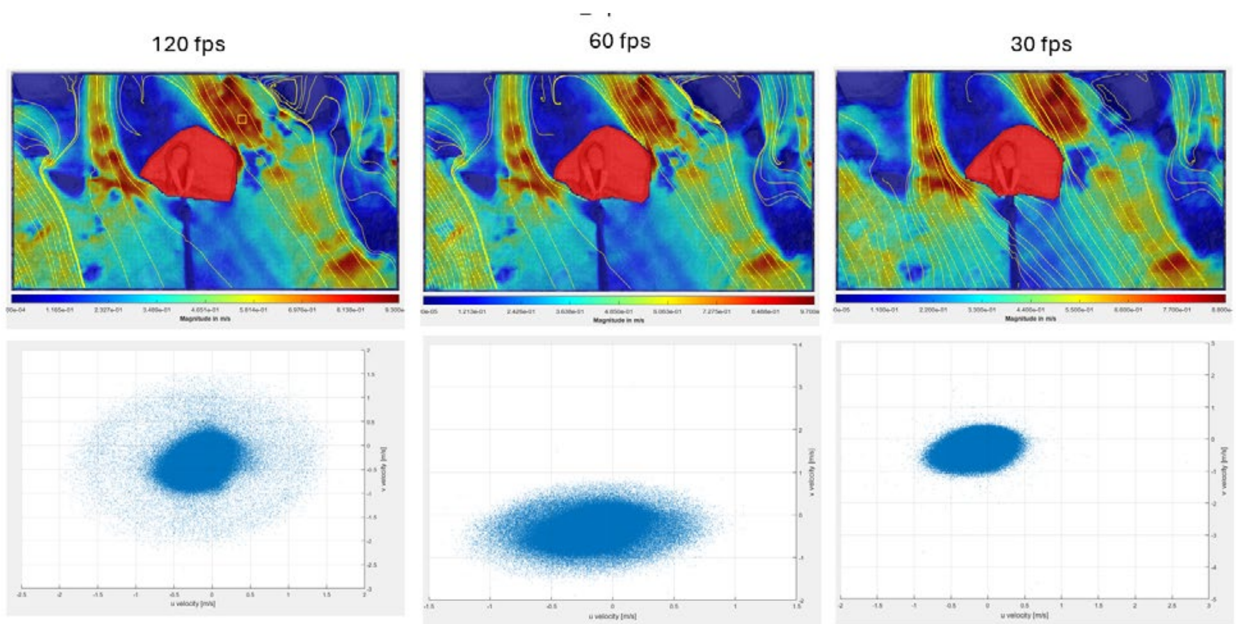

Figure 5. PIVLab outputs of the mean velocity vector mapping at 120 (left), 60 (center), and 30 fps (right) with velocity scatterplot. Video was collected using a GoPro HERO 10. Flow moving from the bottom of the frame to the top. Note: red area in the center of the image is masked, or excluded from processing, and represents where the camera was mounted in the frame.

4.2.2. With and Without Seeding

Seeding for this study consisted of local plant-based material, such as fallen leaves, and purchased wood shavings. All materials were selected to be bio-degradable and nonobtrusive to wildlife. For this comparison, all camera settings remained constant with all data collected on one continuous video. Leafy debris was often of an inconsistent size and shape, making it difficult to evenly distribute and was thus eliminated from repeated use.

The rivers used in the field portion of this study were not turbulent enough and did not have natural surface flow variation to support LSPIV analysis without the addition of seeding material. In unseeded conditions, the lack of distinct surface tracers limited the ability of the PIVLab to identify coherent particle motion, resulting in poor correlation between image pairs. This can be seen through a few different outputs in Figure 6 and Figure 7:

1) Streamlines are represented in PIVLab by solid white lines running parallel to the flow. For the “no seed” conditions, streamlines were either not possible to generate or start/stop in sporadic patterns instead of linearly around the boulders.
2) In the velocity scatterplots, for seeded conditions, there is a much tighter and clearer pattern of where the majority of the velocity points are.
3) While some of the near-field videos were able to produce velocity fields in the highest turbulent areas, all ability to produce velocity data was lost further downstream.

These results highlight the necessity of artificial seeding in low-turbulence rivers to ensure adequate particle density for robust cross-correlation and accurate velocity extraction.

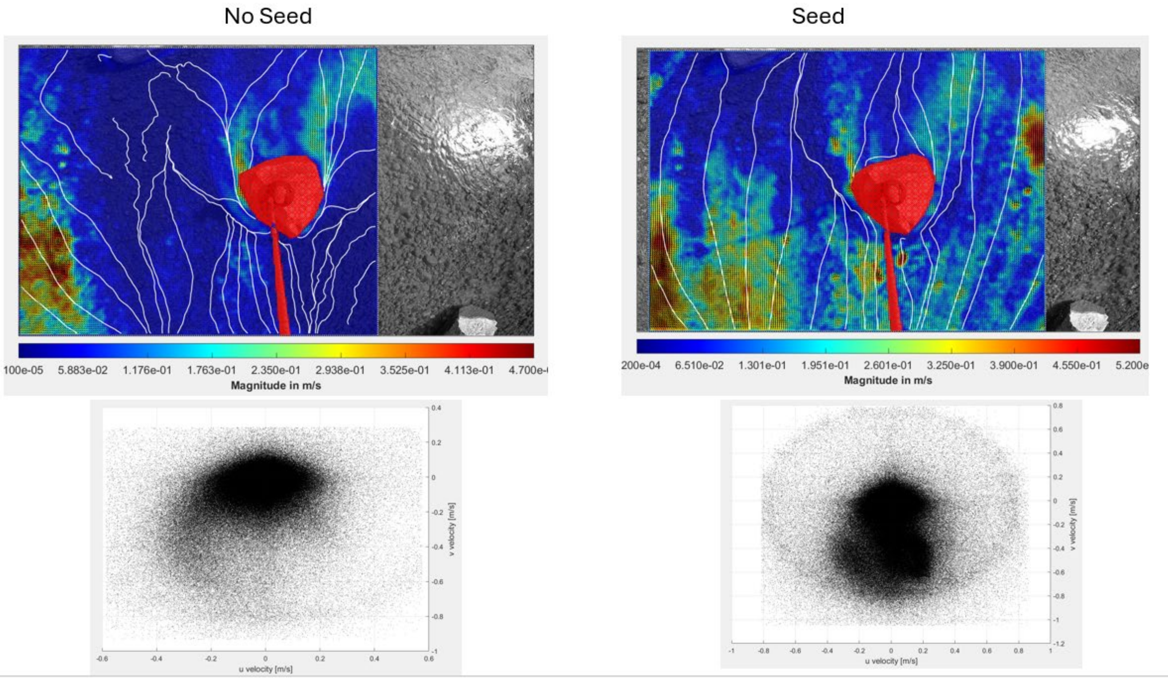

Figure 6. PIVLab output of the mean velocity vector mapping without (left) and with (right) seeding on one cluster of rocks. Video collected with a GoPro HERO 10. Flow moving from the bottom of the frame to the top. Note: red area in the center of the image is masked, or excluded from processing, and represents where the camera was mounted in the frame.

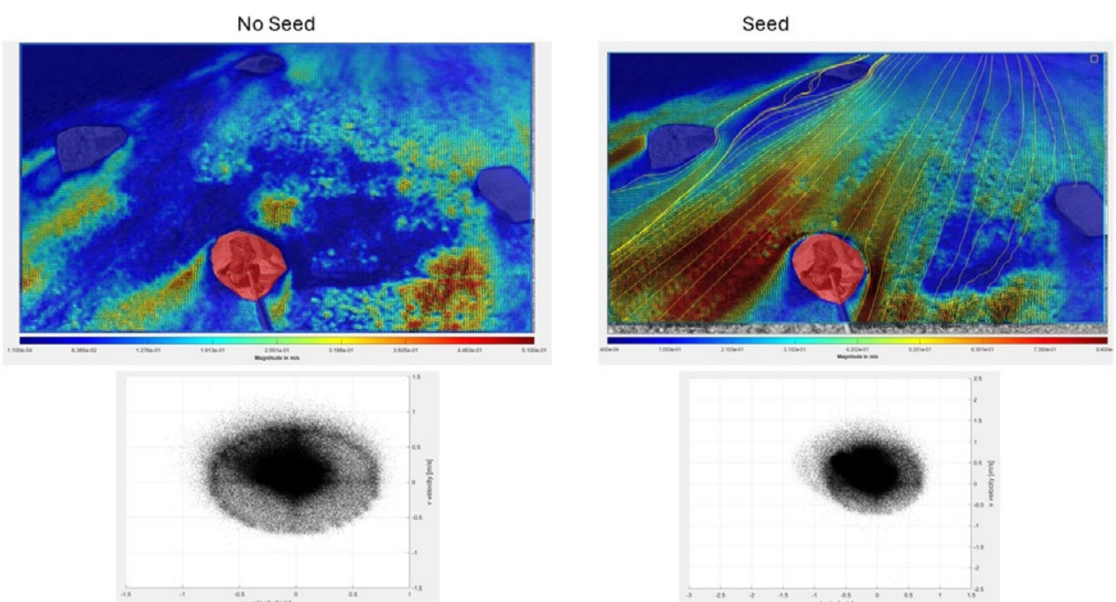

Figure 7. PIVLab output of the mean velocity vector mapping without (left) and with (right) seeding on a separate cluster of rocks on a different day. Video collected with a GoPro HERO 10. Flow moving

from the bottom of the frame to the top. Note: red area in the center of the image is masked, or excluded from processing, and represents where the camera was mounted in the frame.

4.2.3. Cell Phone Videos

While at the Wenatchee site, video was collected using an iPhone 15 Pro. Video was collected from the same boulder location as video collected using the GoPro, however, at a much lower height as the GoPro was able to be raised on an extendable rod. The iPhone video was collected with and without distorted settings enabled. Without distorted settings enabled, or simply a regular video, the iPhone was able to capture video with good agreement to ADV data, with velocities downstream of the boulder matching within 0.1 ft/s (Figure 8).

Both RIVeR and PIVLab include built-in tools to correct distortion from a video. Therefore, to increase the field of vision of the camera, it was decided to collect iPhone data with the zoom out feature enabled on the camera. This creates a "fisheye" effect in the video, with higher amounts of distortion at the edges of the field-of-view. When correcting this distortion during post-processing, known ground coordinates are input into the software to help the program flatten, or correct for, the distortion in the video. However, there was no significant difference between images with and without the distortion correction feature enabled (Figure 9). Therefore, distortion should not be used in collecting LSPIV data without more refined georeferenced tie-in points in 3D coordinate planes.

In all, LSPIV data could successfully be collected and then processed with video from a smartphone under specific conditions. These conditions require seeding and no distortion, and it should be noted that the end result will have a much narrower field of view. Therefore, these limitations indicate that while smartphones may serve as a viable backup when dedicated equipment is unavailable, they should not be considered the primary tool for high-accuracy LSPIV data collection.

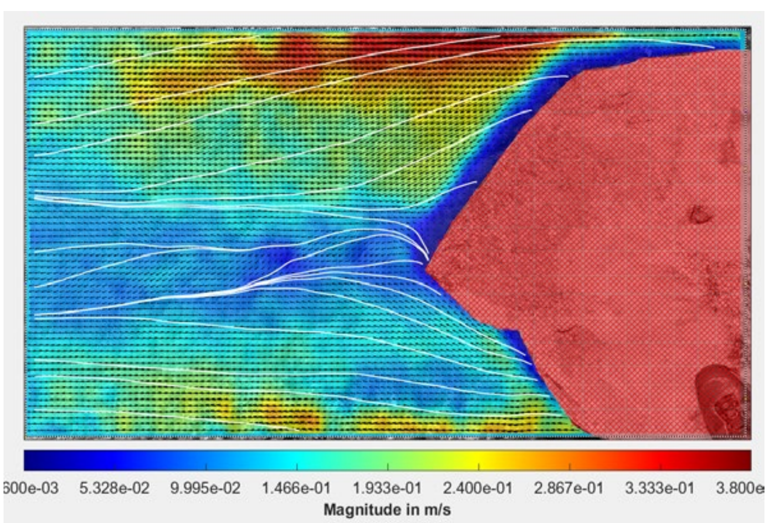

Figure 8. PIVLab outputs from an iPhone 15 Pro with seeding. Flow is moving from right to left. Note: red area in the center of the

image is masked, or excluded from processing, and represents where the camera was mounted in the frame.

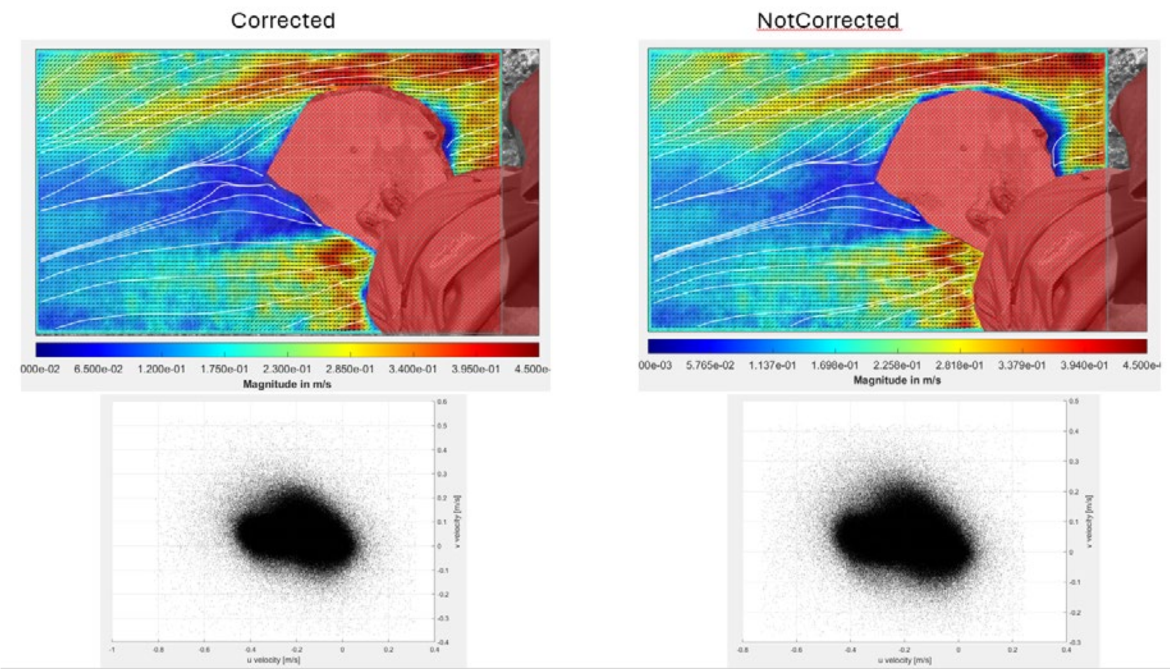

Figure 9. PIVLab output using cell phone at zoomed out (0.6x) distorted setting with (left) and without (right) correction for distortion. Flow is moving from right to left. Note: red area in the center of the image is masked, or excluded from processing, and represents where the camera was mounted in the frame.

4.2.4. Results from TRiVIA

Since all data collected as part of this project utilized close cameras such as GoPro and iPhones, it was not the ideal use-case for TRiVIA. However, it was decided to proceed with this processing method to see if it could still be applied. Similarly to PIVLab, LSPIV data was processed with and without seeding material (Figure 10). This was the same case as tested in PIVLab (Figure 7). Unfortunately, due to the nearfield data collection, TRiVIA was not able to produce full flow-field results as observable by the blank (white) areas in Figure 10.

In June 2025, Reclamation met with the USGS employees who produced TRiVIA to see if the application could be further refined. Since close camera data collection was not the intended use case, there was not much that could be done to refine the output. USGS employees recommend collecting data via UAS or aircraft when using TRiVIA software. Therefore, future work should be expanded to test TRiVIA outputs with the correct data collection method.

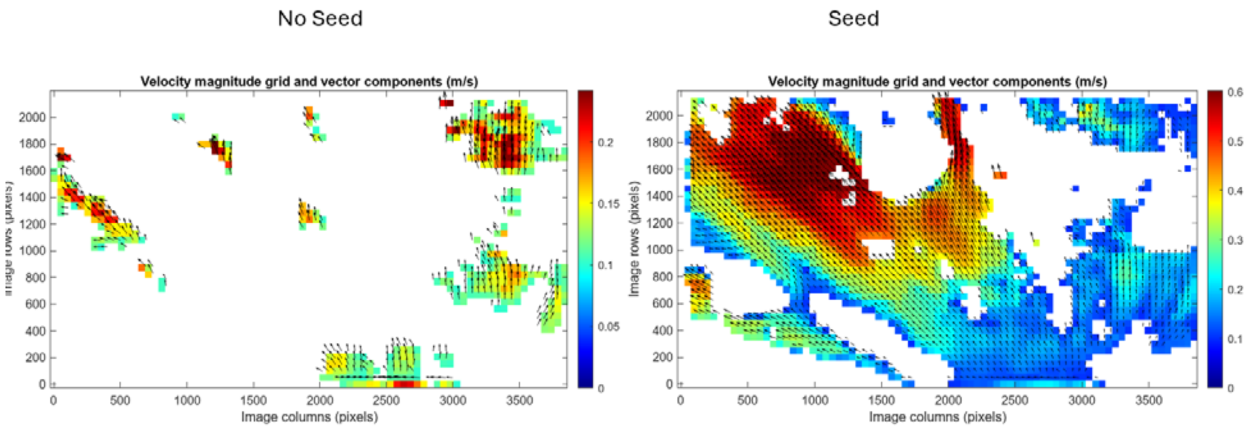

Figure 10. TRiVIA output without (left) and with (right) seeding.

5.0 Conclusions and Future Work

Large-Scale Particle Image Velocimetry (LSPIV) is a technique currently used by Reclamation and other entities to measure surface velocities. This process records particle movement, often referred to as seeding material, at the water surface using video recording devices such as GoPro cameras. From there, frames of the video are extracted and put through a processing software that traces each particle's pathway along the water surface over a known distance. This is used to derive the velocity of each particle, creating velocity maps and streamlines across the surface of interest. Currently, Reclamation's Hydraulics Laboratory uses software called PIVLab and polystyrene bead material.

As part of this project, both field and laboratory sites were tested. For the field testing, LSPIV data was collected both with and without seeding material, and at 30, 60, and 120 fps using a GoPro and phone cameras. For laboratory testing, LSPIV data was collected with three unique seeding materials via three dispersion techniques at 30 and 60 fps using a GoPro camera. Both datasets were processed using PIVLab and TRiVIA software.

- For seeding material: the polystyrene beads were the easiest and most effective at covering a large area within the physical hydraulic model. However, dark water beads were an effective alternative. In the field, even with turbulent flow, seeding material was still necessary. Wood shavings were an effective and easy to source biodegradable seeding material.
- For data collection: the GoPro at 30 fps is best for velocities under 3 ft/s. Using higher frame rates skewed the velocities higher than what corresponding velocity data collected via other means showed at the same location. For velocities above 3 ft/s both the 120 and 60 fps on a GoPro can work well to collect accurate data.

- For data processing: PIVLab is better suited for laboratory use. It is also preferable for field data when data is collected using a camera such as a GoPro mounted on an extendable rod or mobile device cameras, when needed.

As PIVLab had new software components compared to previous versions and TRiVIA was an entirely new software package, new workflows were also created as part of this project for ease of future use and training.

5.1. Future Work

During the span of this project, Reclamation acquired a Wingtra fixed wing UAS. This UAS is LiDAR capable and thus can collect river sections of LSPIV data. Future LSPIV work should include attempting to collect and process LSPIV data with the Wingtra, both in PIVLab and TRiVIA. Other future work should include testing air-entrained flow for use as a tracer in LSPIV. Additionally, LSPIV should be tested in tandem with other data collection techniques such as infrared cameras for simultaneous velocity and scalar measurements. Finally, better quantifying error and uncertainty associated with LSPIV data collection techniques can continue to refine this technique.

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Appendix A

Updated RiVER and PIVLab Processing Workflow

PIVLab and River Quick Guide

Created by Bohman, Larry R., last modified by Engel, Frank on Dec 18, 2017
Edited by Shinbein, Melissa, on April 18, 2024.

RIVeR Software

See also: http://riverdischarge.blogspot.com/p/tutorial.html

Setup

Since RIVeR is a compiled freeware made in the Matlab environment you should:

- Download and install the Matlab Runtime version #R2015a (64-bit)
  >>>Note from Kit, I had to download and install version #R2015b (64-bit) to get RIVeR and PIVLab to work.
- Download the latest version of RIVeR. Note, it takes a while for the .exe to open, so give it a minute.

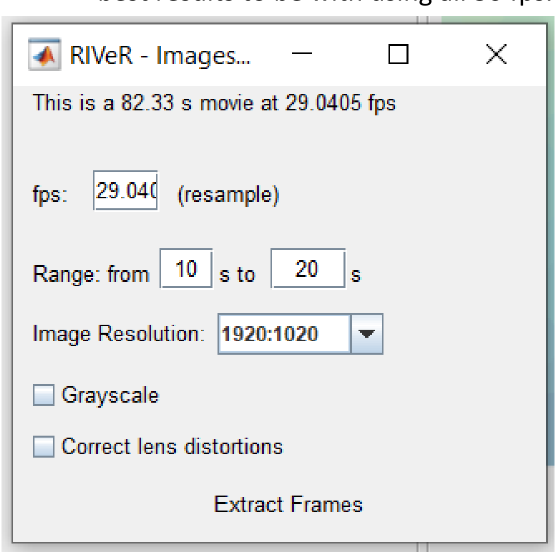
File location/structure: RIVeR cannot process data when in long path files with spaces. Put all folders on the C-Drive (local desktop) while working with the data.

- Decide on a 10-second cut of a longer video (an entire video should be 30-60 seconds). I highly recommend documenting what 10-second cut you decide on using.

Pulling Frames from Video

In RIVeR: **File ► Extract Images From File** (note that filenames CANNOT have imbedded spaces)
Click on the target video file, then **OPEN.**

- Decide on fps (want 15 -25 pixels displacement per pair of images). I have personally found the best results to be with using all 30 fps.



Appendix A- 1. RiVER frame extraction pop up.

Selecting either **Grayscale** or **Color** are equally okay but sometimes using grayscale helps with contrast. Using Grayscale purportedly increases processing times. Actually, PIVLab will convert to grayscale in the background even if you don't. I often process in color so I can see what I'm doing better.

Click on **"Extract Frames"** You'll note the directory with the video now has all the still frames.

PIVLab

Resources: https://www.pivlab.de/; https://www.youtube.com/watch?v=g2hcTRAzBvY

Setup

Input Data ► Import Images

Appendix A- 2. PIVLab prompts for importing images.

Browse (button on middle right). Navigate to FOLDER where sampled images exist. Select folder.

Select the following **image sequencing style**: Time resolved: [A+B], [B+C], [C+D]**.**

- FYI, the other sequence style is used for "classical PIV" which traditionally had 2 cams that were time synced to take pics one after the other (because they couldn't go as fast with 1 cam). That's less important/irrelevant with one camera, and our applications.

Select all images (Ctrl+a). Click **Add.** Select **Import.**

- The image list on the panel on the right side displays the images that you selected. The letters 'A' & 'B' denote the first and the second image of one image pair (= one "frame"). In the lower right corner, you will find a slider to navigate through all frames, and a button (Toggle A/B) to toggle between the individual images within one frame.

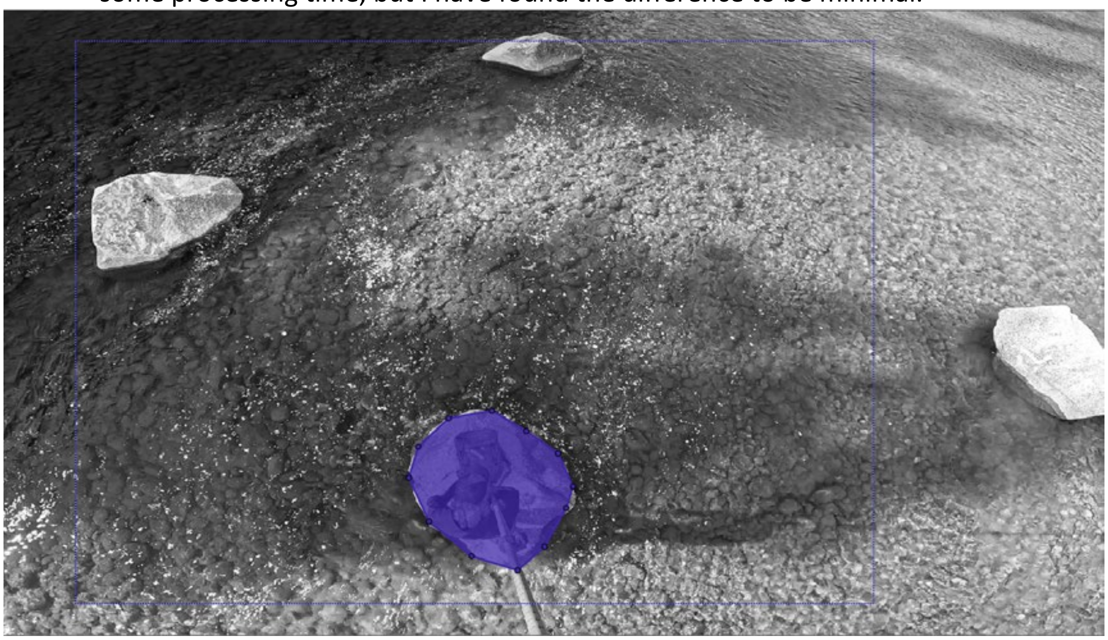
Image settings ► Define Region of Interest (ROI).

- You don't have to have an ROI or Masks, but it will dramatically speed up processing if you exclude "not water". Also, if you don't specify ROI/Mask, you can, and likely will get velocity vectors in regions where there is not water.

Select ROI and then draw a box that encompasses all your reference points (see green-dash area below). Use "Clear ROI" if want to re-draw or click and drag from the corner of the box for different extents. The entire extent box can also be moved from the corners.

Image settings ►Define masks to exclude region from analysis.

- Use Polygon for weird shapes. Double click to close the loop. Repeat this step for the other areas you do not want processed within your ROI.
- Mask areas that you anticipate may move during the time of analysis (such as people or vegetation). You may also mask areas you do not anticipate moving (banks or rocks) to save on some processing time, but I have found the difference to be minimal.



Appendix A- 3. Imported image showing region of interest for PIVLab.

Click on **Copy mask to all frames** (you won't notice any action)

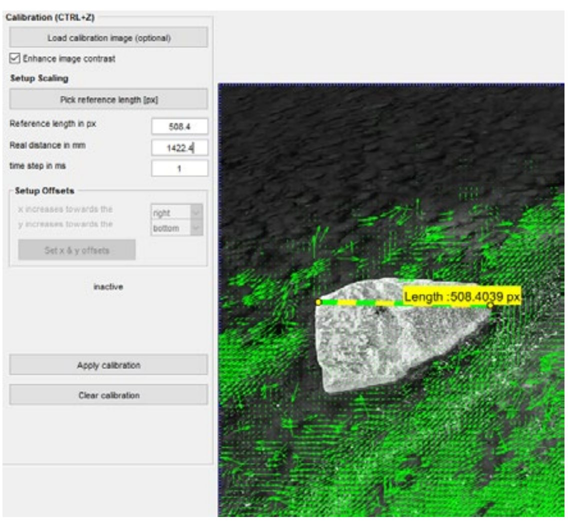
Image Settings ► Image Pre-processing: Contrast-limited adaptive histogram equalization (CLAHE) is enabled by default. This filter locally enhances the contrast in the images. Highpass filtering is also commonly used. Play around with the settings to see how the filters affect the image. Your goal is to produce an image with as much contrast of the moving bits in each Frame as possible. For now, enable CLAHE (20 pix window) and highpass filtering (15 pix window). MDS note: I have had fine results without using the highpass filtering. Do as you please.

Apply and Preview Current Frame (will get result as shown below):

Appendix A- 4. Sample pre-processed output from PIVLab.

Calibration ► Calibrate using current or external image

Pick Reference Length [px]. It will have you draw a line across your point of interest and fill in the related real distance in mm and time step in ms boxes. *Length must be in mm.*



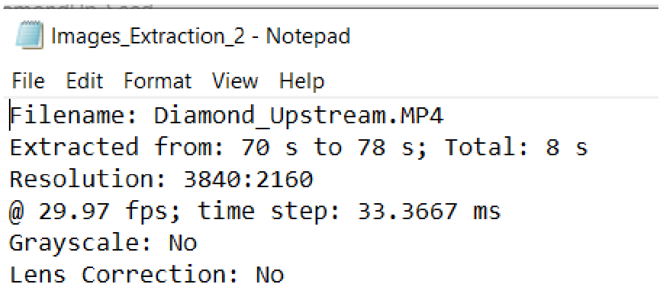
Appendix A- 5. Calibration example.

The time step calculation is as follows:

$$X\ \frac{seconds}{frames} * 1000 = time\ step\ in\ milliseconds$$

Example: $$\frac{1}{30\ fps} * 1000 = 34.4ms$$

Please note, if you use RiVER to generate your stills from the video: RiVER generates a .txt file named “Images_Extraction”. This file contains the frames per second (fps) of the video and the time step in millisecond. You can use this instead of calculating the milliseconds. See below picture for example.



Images_Extraction_2 - Notepad

File Edit Format View Help

```
Filename: Diamond_Upstream.MP4
Extracted from: 70 s to 78 s; Total: 8 s
Resolution: 3840:2160
@ 29.97 fps; time step: 33.3667 ms
Grayscale: No
Lens Correction: No
```

Appendix A- 6. Sample output file from RiVER.

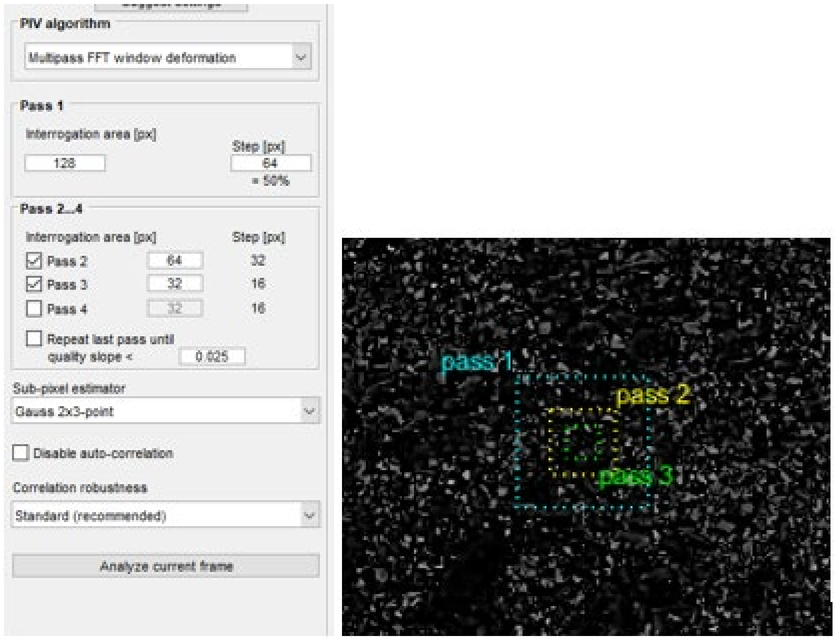
Hit **Apply calibration**.

Analysis

Analysis Settings ► PIV Settings

- To setup the cross-correlation for your image data. PIVlab features two different correlation algorithms, DCC (single pass direct cross correlation) and FFT window deformation (direct Fourier transform correlation with multiple passes and deforming windows).
- Leave **Multipass FFT window deformation** in PIV algorithm box checked as is. Using this algorithm, your data will be analyzed in several passes: The first pass uses relatively large interrogation areas to calculate the displacement of your image data reliably. The larger the interrogation areas, the better the signal-to-noise ratio, and the more robust is the cross correlation. But large interrogation areas will only give a very low vector resolution ("vectors per frame"). That is why you should decrease the size of the interrogation windows in the following passes. The displacement information of the first pass is used to offset the interrogation areas in the second pass and so on. This procedure yields a high vector resolution, a high signal-to-noise ratio, and a high dynamic velocity range. Start with big interrogation areas (e.g. 128 pixels) and decrease gradually in the following passes (e.g. 64 pixels in pass 2).

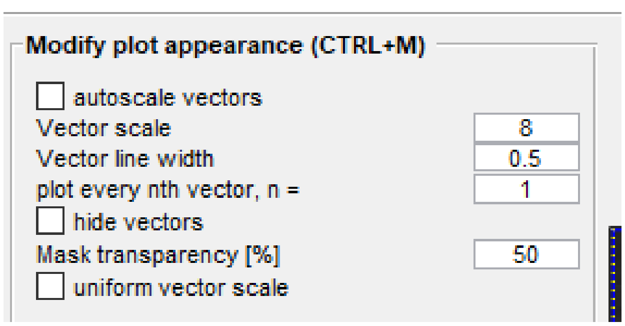
*Change **Pass 1** from 64 to 128 and 32 ◊ 64.* We want displacement to be half the interrogation area (or less). For most videos of rivers, I seem to get good results with 3 passes, 128, 64, 32 (however, the previous recommendation was up to 256. Do as you please).



Appendix A- 7. Input for analysis (left) and sample image of pass sizing (right).

Analysis ► Analyze! ►click on **Analyze Current Frame** if you would like to test and modify anything before. Otherwise, click on Analyze all frames. On the left side of the screen, it will give you updates on total progress and time left.

After processing is complete, to change the vector scales go to: **Plot► Modify Plot Appearance** ►change the vector scale



Appendix A- 8. Plot appearance prompt in PIVLab.

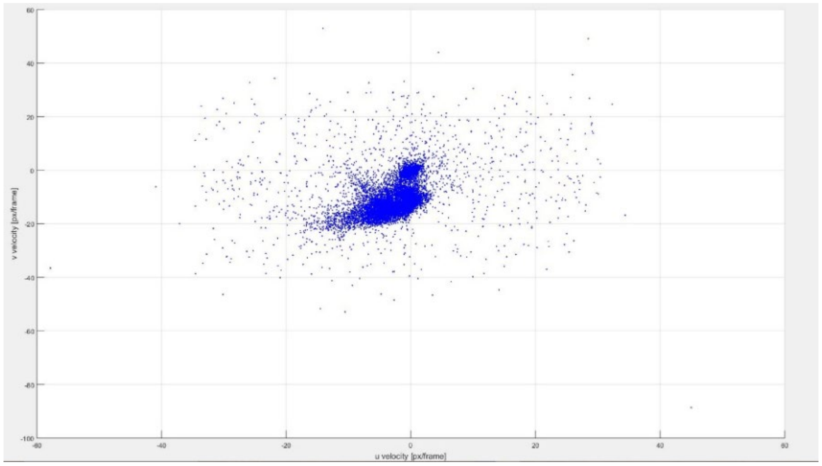
Post Processing

Validation ► Vector Based Validation

Check the box that says **Display All Frames in Scatterplot**

Click on **Select Velocity Limits**

Draw box around the densest part of the data-point cluster (left click – hold – release).



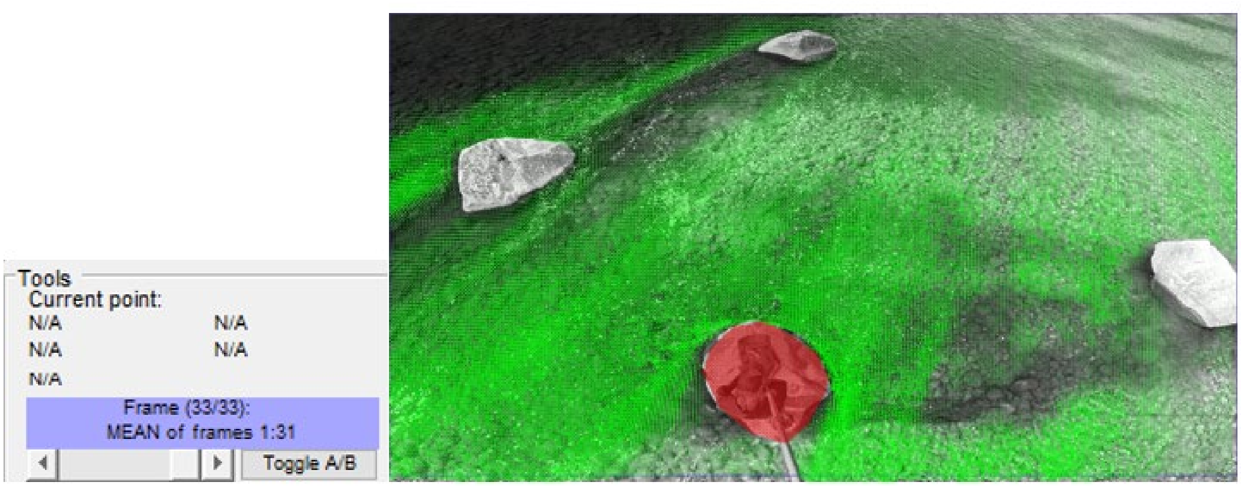
Appendix A- 9. Sample velocity scatterplot generated by PIVLab.

Click on **Apply to All Frames** button (wait, % done displayed)

Output

Plot ► Temporal Parameters then click on the **Calculate Mean Vectors** button.

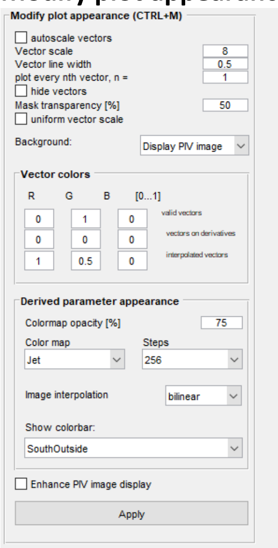
- Now, an additional frame will be automatically added to your session. All masks of the frames you used to calculate this average will be combined. Vectors will be orange in the average frame, if more than half of the original vectors at that spot were interpolated before.
- To save the Means, **File ► Export ► Text file (ASCII)** click on "Export current frame" to only get the means. If you "Export all frames" you will end up with 200+ text files.
- Take a screenshot of the means colormap (see below)



Appendix A- 10. Prompt output demonstrating mean frame was generated in PIVLab (left) and sample mean velocity vector map (right).

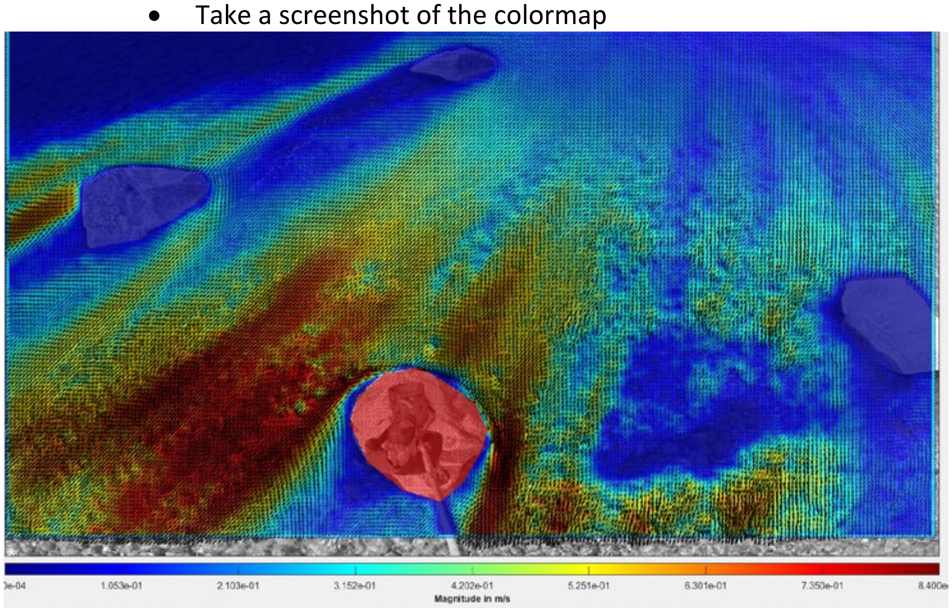
Play around with the other potential outputs in **Plot ► Spatial Parameters**

To create a color map, **Plot ► Spatial Parameters** under display parameter, select Magnitude in m/s and click "Apply to current Frame". To add a color bar and change the color scheme, go to **Plot ► Modify plot appearance**



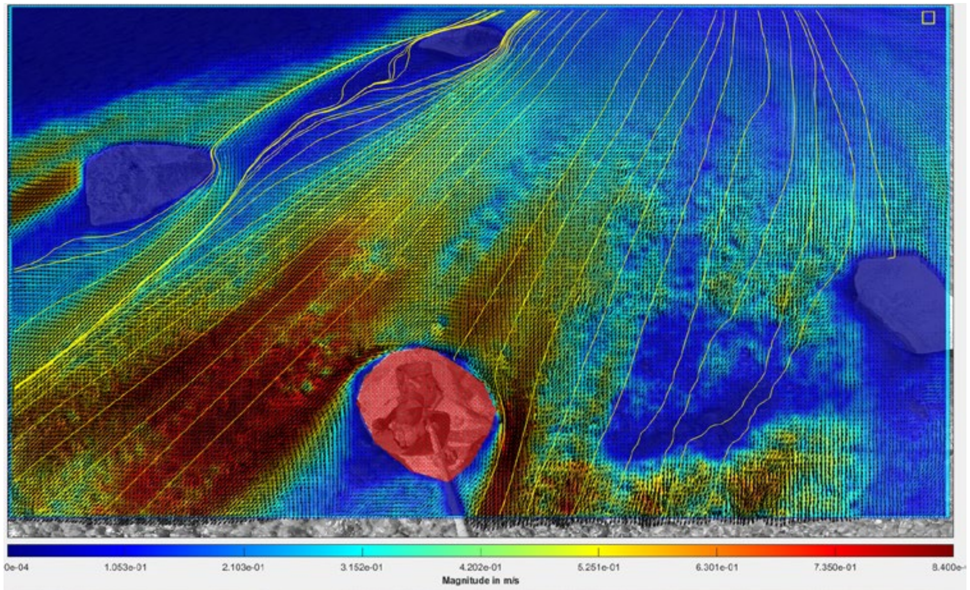
Appendix A- 11. Modifying plot appearance for PIVLab.

- Take a screenshot of the colormap



Appendix A- 12. Sample PIVLab output colormap.

- To add streamlines **Plot ► Streamlines.** Click Draw streamlines or draw streamline rake. Play around with what looks best. It is a learning process.



Appendix A- 13. Sample PIVLab output colormap with streamlines.

File ► Save ► PIVLAB session. It is recommended to save the session in the same folder as the images. The resulting calculations consist of matrices or vectors of displacement for each pair of analyzed images.

You can also output as tecplot and ASCII files. It is recommended, at the very least, to save the means as an ASCII file. Also, take screenshots of whatever visual output you are looking to keep.

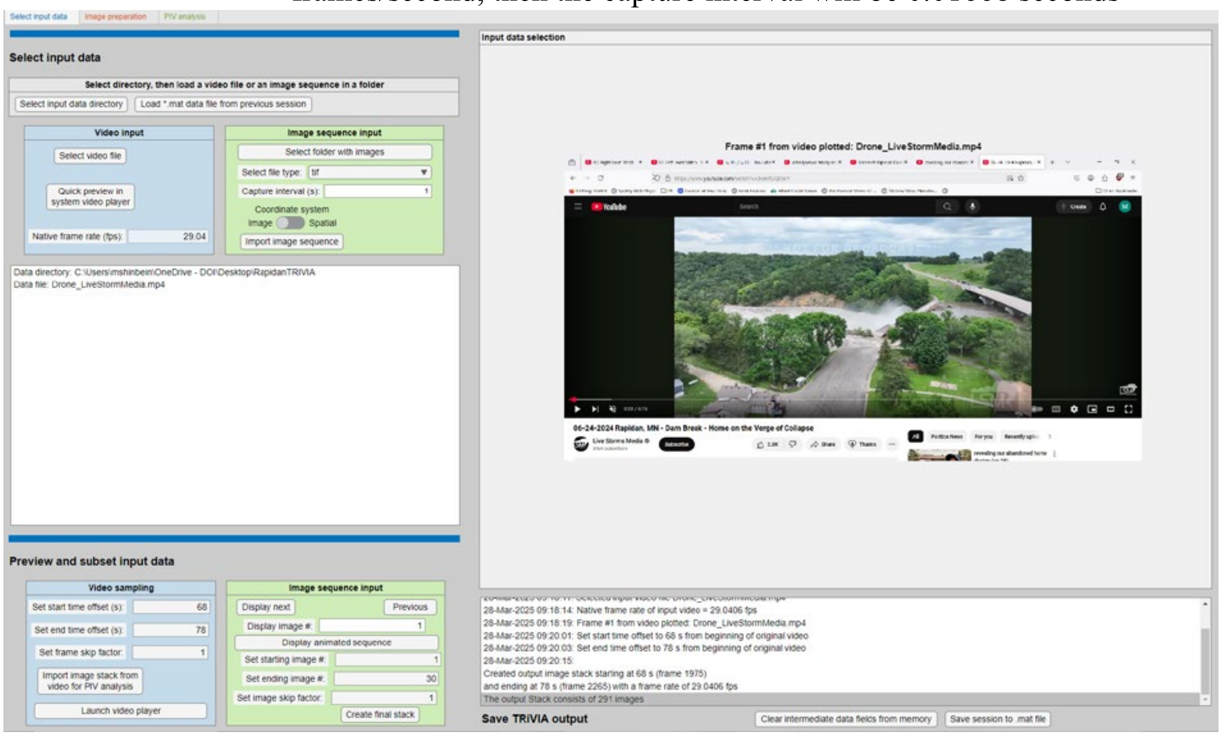
Appendix B

New TRiVIA Processing Workflow

How to Use TRiVIA

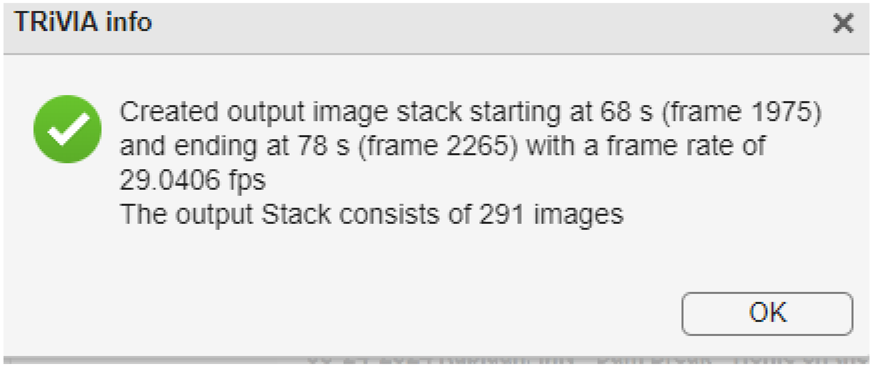
Resources: https://code.usgs.gov/wma/osd/trivia
https://www.usgs.gov/software/toolbox-river-velocimetry-using-images-aircraft-trivia

1) Select Input Data Tab
    a. "Select Input data directory" – add folder where video file is located. It will auto populate the data directory and the native frame rate
    b. IF USING A VIDEO use the blue dialog boxes. IF USING IMAGES use the green dialog boxes.
        i. If using images, make sure to set the capture interval to the inverse of your frame rate. For example, if your frame rate is 29.97 frames/second, then the capture interval will be 0.03337 seconds. If your frame rate is 59.96 frames/second, then the capture interval will be 0.01668 seconds



Appendix B- 1. TRiVIA GUI for importing video.

    c. If you are using video, "Preview and subset input data" -> "Video sampling" put in offset time of interest. Select "Import image stack from video of PIV analysis



Appendix B- 2. TRiVIA pop-up demonstrating processing is complete.

d. If you are using images, in "Preview and subset input data" -> "Image sequence input" set starting image # as 1 and ending image # as the last number in stack, assuming you want to keep all images. Select "create final stack"

2) Image preparation tab

a. Hit "Stabilize images" to populate your images

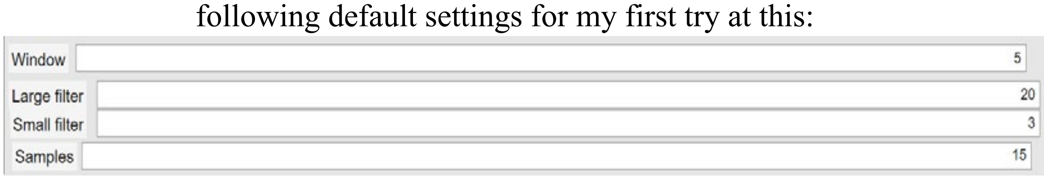
i. Note: The crop images button is a LIE and only works if you are georeferencing something.

b. In the "Select Method to define in-channel region of interest (ROI)" window, select the Digitize option and click the box for "Create region of Interest for PIV analysis". You will need to left click around the region of interest you want. Double left click the last vertex to complete the region. You will see the image update with the new region of interest on the right side of the application in the Image Preparation window.

c. In the "Scale factor only" window, click on the "Measure known length on image" button. Move the line segment to the known length and double left click on one of the line vertices to close this window. Enter the known dimension into the Distance box and click the "Calculate pixel size (GSD)"

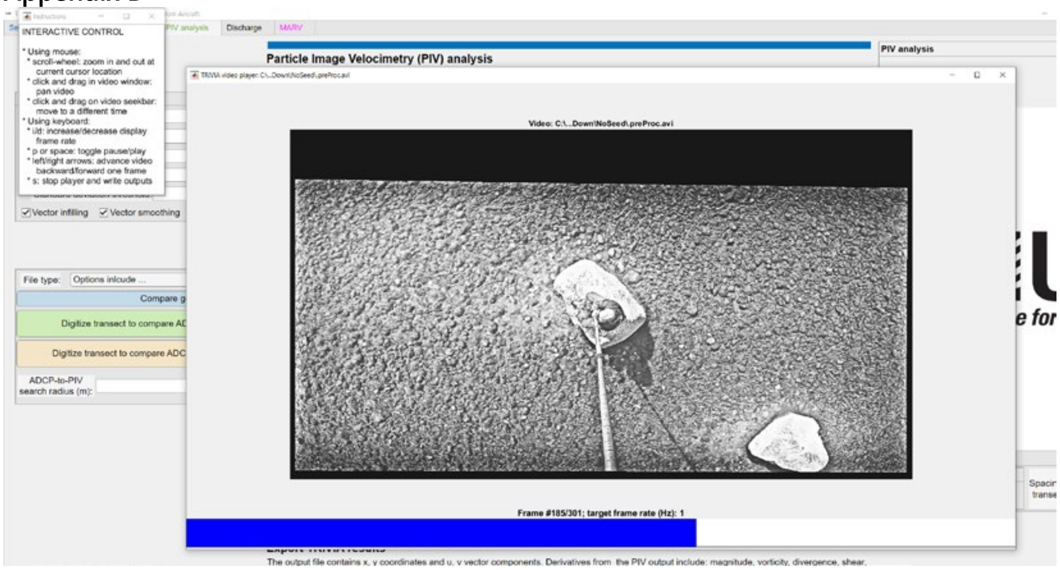
d. In the "Cropping and masking" window, click on the "Mask non-georeferenced image sequence" to apply the mask to the image series. You can click on Visualize raw Stack to see the video play of the images

e. In the Pre-processing window, choose the image enhancement method. I attempted using the ~~FFT bandpass filter option~~ Weiner spatial filter with the following default settings for my first try at this:



Appendix B- 3. Pre-processing filter prompt.

When you have the desired settings selected, click the button for "Enhance images" and it will pre-process the image stack. When this process is done, you can click on "Visualize pre-processed images" to view the results:



Appendix B- 4. TRiVIA output.

3) PIV analysis tab
    a. In the "PIV input parameters" window, change the desired output vector spacing to something smaller than the default value of a meter. Since this application is mainly for higher altitude aerial footage, we need a smaller spacing at a closer scale with our videos. For this initial attempt, I changed the spacing to 0.1 meters
        i. The tutorial document recommends keeping the Velocity limits, Local median threshold, Standard deviation threshold, Vector infilling and Vector smoothing to default values as they can be applied to most cases. If you want to do more passes of the PIV, you can change this from 1 to something greater to get more accuracy. You may need to uncheck vector infilling and vector smoothing as this might give an inaccurate vector field.
    b. In the "PIV processing" window, click the "Perform PIV" button.
    c. After this process is done running, you can display the final output within TRiVIA by clicking "Plot initial output"
    d. You can add streamlines to the output in the "Streamline visualization tool" window
    e. When you are done making the figures, you can click on "Select TRiVIA output file" in the "Export TRiVIA results" window. The file will contain the x (east) and y (north) spatial coordinates of the vector origins in meters and the u (east) and v (north) velocity components of the vectors in meters per second. You can save this data as a .csv file. You can also try clicking on "Calculate derivatives and export" to get more variables like magnitude, vorticity, divergence, shear, strain and direction.

Appendix C

Literature Review

LSPIV Lit Review For Seeding Material

Sensitivity study of large-scale particle image velocimetry measurement of river discharge using numerical simulation

Authors: Alexandre Hauet, Jean-Dominique Creutin, Philippe Belleudy
PDF File Name: 1s2.0S0022169407006518main (1)
Findings:

- Pg 182: Used river images and tracked the natural elements in the footage. Some floating objects with rigid shape and tracked complex evolving turbulent patterns in the flow
    - Tracers as simple squares randomly on the water surface
    - Tracers influenced by the wind out in the field
    - Sun illuminated tracers for the camera to detect
    - Size and color of tracer unknown, bright enough color to be detected. Likely pretty buoyant material to float at the top of the water surface

Capabilities of Large-scale Particle Image Velocimetry to characterize shallow free-surface flows

Authors: M. Muste, A. Hauet, I. Fujita, C. Legout, H.-C. Ho
PDF File Name: 1s2.0S0309170814000657main_1 (1)
Findings:

- "A favorable seeding scenario is when natural tracers float on the free surface. Such situations occur when **light floating debris, foam, ice blocks** are visible at the free surface" pg. 163
- "The present authors tested several environmentally harmless seed materials (e.g. **leafs, mulch, grass, popcorn**), launching approaches (bridges, cranes, confetti machines and cannons), and strategies (multipoint seeding points, transecting the flow)." Pg 163
- "A good candidate for seeding material from multiple perspectives is **Eco-foam** [8], an environmentally friendly packaging material that is more than 95% cornstarch [19,28]. This seeding was successfully tested under laboratory and field conditions [23,24]" Pg 163
- "The surface flow was visualized by **sawdust particles of cypress wood** having a mean diameter less than 1 mm." Pg 164
- "**Ground black pepper** was selected as surface flow tracer, giving sufficient contrast on the white molded surface" Pg 166

Large-scale particle image velocimetry for flow analysis in hydraulic engineering applications

Authors: Ichiro Fujita, Marian Muste & Anton Kruger
PDF File Name: 454455 (1)
Findings:

- Air bubbles and tracked their shadows (Pg 406)
- "Black plastic beads of 2 mm diameter were released for this purpose through several injection points located strategically in the dividing wall." Pg 406
  - Might need smaller diameter particles than this for capturing fine turbulent details
- For the experiment with ice, they used the model ice and "low concentrations of 3-mm diameter block polypropylene beads" for tracking (Pg 408)
  - "For the ice-covered regions, when a continuous layer of black beads covered the water free-surface, low concentration of square-shaped (1cm by 1 cm) white polypropylene particles were included in the continuous layer, to trace the ice flow" Pg 408

River gauging using PIV techniques: a proof-of-concept experiment on the Iowa River

Authors: J.D. Creutin, M. Muste, A.A. Bradley, S.C. Kim, A. Kruger
PDF File Name: 227068657 (1)
Findings:

- Used a naturally occurring foam as a flow tracer created by a waterfall and highly aerated flow at the tow of a sill
- Can use leaves for smaller width rivers
- Not much was mentioned about the size of the tracer foam. They focused on the composition of it with the clays of the river allowing it to form naturally.

Application of large-scale particle image velocimetry (LSPIV) to identify flow pattern in a channel

Authors: Tommy Ekamitra Sutarto
PDF File Name: Application of Large-Scale Particle Image Velocimetry (LSPIV) to Identify Flow Pattern in a Channel
Findings:

- Eco-foam was used as the flow tracer particles. Second time this has been mentioned (pg. 215)
  - "The tracer particles were biodegradable eco-foam peanut which are granular packaging materials made of predominantly corn syrup. These particles have low

inertia and submergence; therefore, they are able to follow accurately local flow movements. The size of the particles was about 2 cm, large enough to be detected by the camera"
    - "The density of the seeding material was in the range between 10 and 30 percent of the surface area"

Remote Sensing Large-Wood Storage Downstream of Reservoirs During and After Dam Removal: Elwha River, Washington, USA

Authors: D. Buscombe, J. A. Warrick, A. Ritchie, A. E. East, M. McHenry, R. McCoy, A. Foxgrover, and E. Wohl
PDF File Name: Earth and Space Science - 2024 - Buscombe - Remote Sensing Large-Wood Storage Downstream of Reservoirs During and After Dam
Findings:

- This source focused on large woody debris analysis and was doing mainly aerial imagery. Nothing was mentioned of LSPIV and seeding particles

Effects of estuarine mudflat formation on tidal prism and large-scale morphology in experiments

Authors: Lisanne Braat, Jasper R. F. W. Leuven, Ivar R. Lokhorst and Maarten G. Kleinhans
PDF File Name: Earth Surf Processes Landf - 2018 - Braat - Effects of estuarine mudflat formation on tidal prism and large-scale
Findings:

- Floating plastic particles used to obtain surface water velocities (pg. 420)
    - Did not talk about the size of these particles or any other characteristics of them
- Focused on mud primarily

A framework to facilitate development and testing of image-based river velocimetry algorithms

Authors: Carl J. Legleiter and Paul J. Kinzel
PDF File Name: Earth Surf Processes Landf - 2024 - Legleiter - A framework to facilitate development and testing of image-based river
Findings:

- Numerical model called SHIVER that used the following particle parameters:

A FRAMEWORK TO FACILITATE DEVELOPMENT AND TESTING OF IMAGE-BASED RIVER VELOCIMETRY ALGORITHMS ESPL–WILEY 1365

TABLE 1 Summary of experimental design listing key parameters and their values for each component of the three main components of the SHIVER framework.

Parameter	Value(s)	Units	Number
Particle map			
Particle concentration n	1	Per 16-pixel IA	
Particle radius r_p	3	pixels	
Rendering radius r_r	20	pixels	
Image background noise σ	10	Digital numbers	1
Hydrodynamic model			
River discharge	90, 191, 255	m^3/s	
→ reach-averaged velocity magnitude	0.81, 1.14, 1.27	m/s	3
Synthetic image generator			
Image sequence duration	60, 30, 15, 10, 5	s	5
Frames skipped	1, 2, 3, 4, 5, 6, 7, 8	-	
→ Frame rate	4, 2, 1.333, 1, 0.8, 0.667, 0.571, 0.5	Hz	8
Interrogation area size	16, 32, 48, 64, 80, 96, 112, 128	pixels	
→ PIV output grid spacing	1.2, 2.4, 3.6, 4.8, 6.0, 7.2, 8.4, 9.6	m	8
		Total PIV analyses	**960**

Note: The number of values of each parameter is shown in the final column and the product of these is the total number of PIV analyses performed in this study.

Appendix C - 1. Particle parameters used in numerical model.

- Nothing else is said about the seeding particles they used in the program

THE REMOTE MONITORING OF SURFACE VELOCITY, BATHYMETRY AND DISCHARGE IN RIVERS AND OPEN CHANNEL FLOWS

Authors: Erika D. Johnson
PDF File Name: edj28
Findings:

- Small buoyant particles
- Small Stokes number (St# = 0.003)
- "The particles that were imaged in these experiments were **Pliolite VTAC-L particles**, which are manufactured by OMNOVA. While these particles have a mean specific gravity of 1.03, there is a distribution of individual particle density, as evidence by their behavior in water. Particles that float were preferentially selected for use in the experiments. The particles were sifted between a series of sieves and only particles in the range 420 - 600 microns (0.42 – 0.6 mm) were used in this study." (pg. 23)

Growing Forced Bars Determine Nonideal Estuary Planform

Authors: J. R. F. W. Leuven, L. Braat, W. M. van Dijk, T. de Haas, E. P. van Onselen, B. G. Ruessink, and M. G. Kleinhans
PDF File Name: JGR Earth Surface - 2018 - Leuven - Growing Forced Bars Determine Nonideal Estuary Planform
Findings:

- Used white floating particles with 2.5 mm diameter (pg. 2976)
- Nothing else has been mentioned for the description of the particles
    - White seems to be a common color for the particles so the camera can track them

Incipient Tidal Bar and Sill Formation

Authors: J. R. F. W. Leuven and M. G. Kleinhans
PDF File Name: JGR Earth Surface - 2019 - Leuven - Incipient Tidal Bar and Sill Formation
Findings:

- "White polystyrene particles (diameter approximately 2.5 mm) on the water surface" pg. 1766
- Nothing else mentioned for the parameters of the particle

Experimental System for Real-Time Discharge Estimation Using an Image-Based Method

Authors: Alexandre Hauet; Anton Kruger; Witold F. Krajewski; Allen Bradley; Marian Muste; Jean-Dominique Creutin; and Mark Wilson
PDF File Name:
krugeretal2008experimentalsystemforrealtimedischargeestimationusinganimagebasedmethod
Findings:

- Waterfall created foam which acted as a tracer for the LSPIV study (pg. 2)
- Typical size of the aggregates of foam was about 5m and distance between the aggregates was 10m (pg. 2)
    - This was another instance of natural foam being used as a tracer

Defining the Limits of Spectrally Based Bathymetric Mapping on a Large River

Authors: Carl J. Legleiter and Ryan L. Fosness
PDF File Name: remotesensing-11-00665-v3
Findings:

- Does not really mention the tracer used. This was a suspended sediment study and some of the data related to it can be found on page 7 in table 1

Large-scale particle image velocimetry for measurements in riverine environments

Authors: M. Muste, I. Fujita, and A. Hauet
PDF File Name: Water Resources Research - 2009 - Muste - Large-scale particle image velocimetry for measurements in riverine environments

Findings:

- Mentions foam, leaves, or artificial seeding can be added to surface for collecting measurements (pg. 4)
- Pg 9, “vigorous kolks, boils, and ripples generated by the large-scale turbulent eddies moving over the bed forms and roughness will be observable at the free surface. These free surface perturbations act as reflectors of the sun or other dominant ambient light playing the role of natural seeding for the LSPIV measurements”
- Pg 9, “second type of tracer that can occur naturally during floods is created by large-scale turbulent eddies entraining sediment throughout the flow depth”
    - Creates sediment clouds
- Third type is floating debris carried by the stream (pg. 9)
- Study used “biodegradable packaging particles” pg. 9

Table 1. Comparison of Selected Characteristics of the Acoustic Doppler, Radar-, and Image-Based Velocimeters for Riverine Environments

Technique or Characteristics	Acoustic	Radar	Image
Measurement type	Profile: along the acoustic beam path (verticals); three-component velocity.	Point: at the intersection of the beam with the free surface; one-component velocity.	Surface: instantaneous vector field at the free surface; two-component velocity.
Flow tracers	Small particles usually naturally suspended in the water column.	Small surface waves created by wind or by flow turbulence at the free surface.	Foams, debris, ice floes, and specular reflections on the free surface deformations (waves, boils, kolks). Added seeding.
Operating constraints	Instrument probe in contact with the flow. The flow assumed horizontally homogeneous.	The ratio between the Incident electromagnetic and water wave wavelengths within specified range. Instrument aligned with the dominant velocity.	Survey of minimum six points within the imaged area. Occasionally, additional seeding and illumination.
Output quality	Good spatial and temporal resolution. Inaccurate for very slow flows.	Limited spatial and temporal resolution. No reverse flows. Inaccurate for very slow flows.	Good spatial and temporal resolution.

Appendix C - 2. Table from article showing technique and seeding type tested.

- Page 11

Remote monitoring of volumetric discharge employing bathymetry determined from surface turbulence metrics

Authors: E. D. Johnson and E. A. Cowen
PDF File Name: Water Resources Research - 2016 - Johnson - Remote monitoring of volumetric discharge employing bathymetry determined from (1)
Findings:

- “The laboratory flow is seeded with **small buoyant Pliolite VTAC-L particles**. The particles have a specific gravity, SG 5 qi/q 5 1.03, where qp is the particle density, and

were sieved to a particle diameter (dp) range of 0.42–0.60 mm. The particle Stokes number is small," (Page 7)
    - Passive tracers
    - Second time this type of seeding material was used, but both are from same author. Must have worked well enough to be used multiple times.

Remote Sensing of River Bathymetry: Evaluating a Range of Sensors, Platforms, and Algorithms on the Upper Sacramento River, California, USA

Authors: Carl J. Legleiter and Lee R. Harrison
PDF File Name: Water Resources Research - 2018 - Legleiter - Remote Sensing of River Bathymetry Evaluating a Range of Sensors Platforms
Findings:

- Does not mention LSPIV and seeding material, mainly a LiDAR study
- Does have information on the suspended sediment sizing they looked at (page 11)