QUANTIFICATION OF HYDRODYNAMIC VARIABILITY
IN SURFACE AND NEAR-BED VELOCITIES
USING THERMAL INFRARED CAMERAS AND
IN-SITU VELOCITY PROFILERS

by

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ABSTRACT

The study of fluid mechanics and its applications is a growing and vastly changing field. The ability to determine how water moves and how this movement causes the bed underneath to react is still very uncertain. Many studies have been performed using in-situ velocity profilers to determine some of the attributes, less have been performed using particle image velocimetry from cameras, and even less have been done comparing the two with the use of infrared cameras. Developing relationships between the surface and sub-surface velocities, vorticity, and turbulent kinetic energy can help us further understand and predict the flow of water, disruption of sea beds and protect our coasts. Velocity, sediment density, and camera imaging data were gathered during the spring of 2011 at the St. Jones Reserve in Dover Delaware and all information for this study was taken from April 17th of that year. Comparisons between different instruments measuring velocities were made using the forward looking infrared (FLIR) Infrared camera software paired with electromagnetic current meters (EMCM) to find velocities and ultra-sonic distance meters (UDM) to gauge water depth.
1.1 Significance of Research

The way fluid moves from place to place, how it rises with the tides, and the manner in which it erodes our shores is in many instances hard to quantify. Many instruments have been developed and used to observe sub-surface flow at one point, and they have been extremely useful. The main problem they face, however, is built right in the design. They can only utilize that one area of flow and cannot provide a spatial understanding of surface flow. This is where particle image velocimetry (PIV) gains its advantage. Using cameras and analyzing changes in the images frame-by-frame, acquisition of quantitative information can be found over a wide area throughout an extended time series (Holland et al., 1997).

Once the velocity vectors are stored in a concurrent time series, higher order calculations can be conducted. This thesis will explore the vorticity of the flow using these velocity vectors, but turbulent kinetic energy and its rate of dissipation can also be found to help draw conclusions. With the increases in precision and speed of cameras being used for this purpose today, it is possible to resolve even the most complex flow without the risk of much error (Eckstein et al., 2006). The ultimate goal is to increase our knowledge of how flow interacts with a tributary through the tidal sequence in a quantitative and numerical way.
1.2 Scope of Work

This study quantifies the hydrodynamic variability of flow on the water surface of a small tidal channel and compares it to in-situ data. In order to do this, five-minute video files from a FLIR infrared camera were utilized. Due to the computing power and memory of the computers, only a 150 frame (about 30 second) file could be processed at one time. Before analysis, a rectification of the images due to the lens attributes as well as the orientation of the camera needed to be done and is described in the methods of analysis. Following rectification, PIV was conducted on the frames and analyzed. This was done using a fast fourier transform (FFT), a method of analysis that converts from the time (or space) domain into the frequency domain. This essentially deconstructs a series of values into its components labeled by different frequencies. This method is used as it increases the speed of computing as compared to a direct correlation process. Once velocity fields are created and their components stored, an analysis of vorticity can be done. Vorticity is a measure of the local spinning of the fluid through space. The equation for vorticity for two-dimensional flow is shown as,

$$\vec{\omega} = \nabla \times \vec{v} = \left( \frac{\partial}{\partial x}, \frac{\partial}{\partial y} \right) \times (v_x, v_y) = \frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y}$$

where vorticity equals the cross product of the del operator and the velocity vector. As shown, vorticity is a subtraction of its partial derivative components of velocity with respect to space. Finding this value can show us eddies and how frequent/persistent they are present in the flow. Finally, a comparison of results to coincident in-situ data instruments was done to see if and how the two methods of analysis are comparable.
Chapter 2

FIELD SITE BACKGROUND

In the spring of 2011 a study was conducted in a tributary tidal channel in the Delaware National Estuarine Research Reserve (DNERR) near the St. Jones River. This study was done in an attempt to gather data to further our knowledge of the spatio-temporal hydrodynamic variability in a tidal channel. During this study, measurements were taken using: electromagnetic current meters (EMCM), optical backscatter sensors (OBS), acoustic water level sensors (AWLS), acoustic Doppler current profilers (ADCP), ultrasonic distance meters (UDM), and Aqua TROLL sensors. Additionally, both a Sony RGB color camera, as well as a FLIR infrared camera was used to take video sequences.

While both the EMCM and the ADCP sensors collect velocities of the flow, the latter collects data in three dimensions while the EMCM utilizes only two-directional flow. The EMCMs are in water sensors that induce a magnetic field around a central sensor head. They give two-dimensional readings of velocity and were oriented to be along stream (positive x is to the right) and cross stream (positive y directed downwards or towards the camera) when looking at the original RGB image. The EMCM’s recorded data continuously and 10 minute averages of velocity both along stream and cross-stream were taken for each.

The OBS evaluates the murkiness of the water or the suspended sediment concentration while the UDM provides water depth measurements. Finally, the Aqua TROLL is able to determine the pressure, temperature, and specific conductivity of the
flow through the channel. For the purpose of this paper, a utilization of the EMCM and the UDM will be used as in-situ data to compare with the PIV analysis. Ten-minute averages of the sampling from these instruments were used in comparison with the PIV data.

Although RGB cameras are easier to understand spatially with the naked eye, PIV code relies on texture differences in the image to create a velocity field. Infrared cameras have the ability to use the heat signatures in the flow to amplify these textures, which is the reason the FLIR infrared camera was used in collection of data for PIV processing. At this field site, these two cameras were mounted above the channel side by side. Images from each are shown in Figure 1.
Figure 1. A snapshot from the RGB camera (top) and FLIR camera (bottom) are shown.
Both of the images were taken at about the same time and give a distinction between each camera’s capabilities. The RGB image renders the ability to see the bridge path on the left side of the image as well as a more complete picture of the flow, while the infrared camera is a bit more zoomed in to pick up small texture changes in the flow over time. Additionally, C1, C2, and C3 show the locations of the EMCM and AWLS sensors that were used to compare data. These EMCMs were located between 10 and 15 centimeters from the bed of the channel, so velocities will not be, and are not expected to be exactly concurrent with PIV results, but general flow direction should hold.

The cameras were set up with left side of the image being true north and the top being east. As the tide comes in and the flow rises, water enters the tributary from the south, or right side of the image.
Chapter 3

METHODS OF ANALYSIS

PIV, or particle image velocimetry is the process by which one takes a video sequence of any form, in this case infrared, and creates a field of velocity vectors throughout the time sequence. This information can be used to create a similar flow field of vorticity and analyzed to quantify turbulent kinetic energy. However, before the vector field can be made, the frame to be analyzed must be rectified onto an x-y plane.

3.1 Image Rectification

PIV with one camera can only be conducted on an image sequence in two dimensions. Because of this, the raw images generated from the infrared camera must be altered to fit this mold. The image as is contains two types of necessary fixes. The first has to do with the camera itself. All camera lenses have a certain curvature in order to pick up a wider degree of visual information. This skews the image and would alter the velocity vectors, especially on the edges of the frame. The second correction has to do with how the camera is oriented relative to the area it is trying to capture. Since the camera was not pointing straight down on the field of view, there is a registration for which the top of the image is stretched more than the bottom and depth in the y direction is skewed. To correct this, a process called georectification must be done.
3.1.1 Camera Lens

In order to correct the distortion due to the camera lens, it must be determined to what extent the lens is non-linear. To do this, a field of white dots was created that are spaced in a perfectly linear fashion in both the X and Y directions. Once this is done, a picture is taken of this field with the camera being used in the experiment. As can be see in Figure 2 below, the camera used for this study did not have a very extreme distortion due to the lens, though it is still important to fix as to minimize error.

Figure 2. Picture of the white dots board before the image has been altered to account for the curvature of the lens.
3.1.2 Georectification

The next variable of the camera that must be addressed is its orientation to the ground. Because of the way that the field site was set up, a comparison between ‘real world’ and local coordinates must be conducted. The first step here is having a well-surveyed site using highly accurate GPS equipment, and the second is to have many of these fixed survey points in the field of view of the camera. These surveyed spots are known as ground control points (GCP’s).

Figure 3. RGB camera snapshot of the tributary at a relatively low tide. The GCP’s can be seen in the tributary. The FLIR camera used in PIV analysis is mounted next to the RGB camera.
Shown in Figure 3 above is a snapshot taken from the RGB camera that was set up right next to the infrared camera used for this analysis. All of the poles with the wooden blocks on top are GCPs. In addition to these blocks, the cameras and locations of sensors were surveyed and their positions recorded for further use. It is important to note that the surveying was done in 3-dimensional space and it is crucial to know the height of the GCP’s as well as the camera. Once the ‘real world’ coordinates are established, a local coordinate system is set up using the field of view of the image. Once the image is uploaded to Matlab, ginput (a tool for finding pixel location) can be used to determine the proximity of the GCP’s to each other in the image. The next step is to input the camera’s variables such as tilt, azimuth and roll. These variable are initialized based on expected values from a visual inspection of the setup and solved further to solidify values once the rectification code is run. Executing the code in Matlab, the video sequence is rectified frame by frame onto an x-y plane, making PIV possible. Figure 4 shows a single FLIR frame before and after rectification. Because the code rearranges the frame to be concurrent with the real world coordinates, the rectified image appears to be rotated 90 degrees clockwise and flipped from top down on its x-axis.
Figure 4. An un-rectified (top) and georectified (bottom) image is shown.
3.1.3 FFT Smoothing

Fast Fourier Transform (FFT) is used to compute DFT, or Discrete Fourier Transform. DFT takes samples from a function that are equally spaced and converts them into coefficients, which are then organized based on their frequency. This function transforms data from a time domain to the frequency domain. In a video sequence, there are different frequencies for every level of light intensity. Working in gray scale imagery, black and white are the extremes on either side with any strength of gray falling in between. Many video sequences have static or ‘noise’ that produce what would look like texture to a PIV program, but is simply bad data. In order to have clean frames, a low pass filter is used to ‘smooth’ the image. What this does is it changes the image file into the frequency domain using FFT and eliminates the high frequency static to whatever threshold is deemed appropriate. Just as the search window and interrogation window must be precise, the smoothing must be done correctly. If the image is too smooth, much of the natural texture of the surface will be lost making eddies and minute changes in velocity disappear. If no smoothing is done, however, there will be texture analyzed that simply was not there in the real world. Figure 5 shows an unsmoothed, well-smoothed, and overly smoothed image respectively.
Figure 5. An un-filtered, moderately filtered, and well over-filtered image are shown on top of each other for comparison.
It is necessary to note that since a form of FFT will be used in the particle image velocimetry, the analysis will again occur in the frequency domain. This is important because the PIV code can more accurately utilize the lighter colored pixels, or higher frequency, than the darker low frequency pixels. In order to maximize the accuracy of the results, the image colors in many cases need to be inverted, which will be noted later in the results section.

3.2 PIV Variables

Particle image velocimetry (Raffel et al., 1998), especially with the use of an infrared camera (Puleo et al., 2011), relies on the ability to follow specific surface textures throughout time. In order to do this, two main variables must be established; the search window and the interrogation window.

3.2.1 Interrogation window

The frames that are being analyzed for this project are 512x512 pixels. With this information, it is crucial to decide exactly how many square pixels are appropriate to try to follow through time. This can be difficult since the flow is ever changing in both direction and speed. If the interrogation window is too small, that 1x1 pixel could potentially be found everywhere and would not follow the true direction of the flow. On the flip side, if the interrogation is too large, after a second or even half a second, that image could have, and most likely will have changed shape to the point of non-recognition. Because of this, much trial and error was needed to zero in on the decided values. With a 512x512 area, it was determined to use 32 grid points in both the x and y direction, each 16 pixels away from each other to ensure best results. To have a standard 50% overlap, 32x32 pixel boxes became the interrogation window.
3.2.2 Search window

The search window is equally important, however much simpler to determine. This variable is dependent only on the maximum distance that the decided interrogation window can travel from frame to frame. The maximum velocities were estimated using the in-situ data as well as visual observation to be at the very most 0.5m/s. Using field of view of about 2.5 meters in the X and Y directions, a single particle could travel no further than \((0.5\text{m/s})/(2.5\text{m})\) or 20\% of the screen, which equates to 102 pixels per second. Using a camera with a frame rate of 6.25 frames/second, a pixel should not appear further than 16 pixels away from one frame to the next, giving us a 16x16 pixel search window.
Chapter 4

RESULTS

4.1 Particle Image Velocimetry

PIV and concurrent analysis was conducted on three different video sequences at different times in the tidal cycle in order to have a better understanding of how accurate the function is compared both to itself, as well as in-situ velocity profilers. Data sets are being used from April 17th, 2011 at 0800, 1400, and 1700 hours. Each of the times have slight, but specific alterations to the Matlab code in order for it to run properly. The PIV code used was, *A robust phase-correlation based motion estimation algorithm for PIV* (Thomas et al., 2005).

4.1.1 Analysis at 0800 hours

At 0800 hours the water level of the tributary was 1.2 meters and increasing, as this is at the tail end of inflow. Since it is approaching slack tide, the velocities are relatively low. Due to this factor, simply analyzing frame-by-frame did not move textures enough, so each frame was compared to the frame two ahead of it to double this texture movement. Additionally this image used a moderate FFT smoothing and the image was inverted for better results. Figure 6 of the un-rectified image followed by the rectified image ready to be analyzed is show below.
Figure 6. Un-rectified (top) and rectified (bottom) image for the 0800 hour video sequence.
While watching the raw video footage, it is clear that the flow in this sequence should be traveling towards the bottom of the image, as it is during the inflow rise of tide. Alterations were made to the code to allow for it to run without administering values to the voided space on the top left and bottom right of the image. As can be seen in Figure 7 below, the flow, at least for a single frame, seems to follow what the eye sees in the raw footage. The magnitude of the vectors is varying, but generally comes in just around 0.1 m/s. Due to the varying temperatures causing both dark and light pixel windows, the PIV code has some troubles making a full frame of accurate vectors.

Figure 7. Single Frame of PIV analysis for 0800 hour video sequence.
4.1.2 Analysis at 1400 hours

At 1400 hours the water level of the tributary was 1.0 meters and dropping rather quickly. Unlike that of 0800 hours, the velocities at this time were significantly quicker. To account for this change, it was necessary to revert back to analyzing each frame with its immediate predecessor. This eliminates the need to change search and interrogation window variables. Additionally, a slight increase in smoothing proved to render a better vector field. Due to the look and light intensity of this video file, it was not necessary to invert the image colors as it was for the others. Figure 8 of the un-rectified and rectified image ready to be analyzed is shown below.
Figure 8. Un-rectified (top) and rectified (bottom) image for the 1400 hour video sequence.
The video sequence for this time shows a clear and strong flow towards the top, or out of the tributary. As this flow is during some of the heaviest ebbing flow, most if not all velocity vectors should be facing the same direction. As can be shown in Figure 9, velocity vectors show a general shape concurrent with a visual inspection of bottom to top. With vectors reaching 0.25m/s, the speed is much greater than the other two observation times. Again, variability in color of the pixel ‘textures’ cause the PIV to render some incorrect velocities in certain frames.

![Single Pass PIV at 1400 Hours](image)

Figure 9. Single Frame PIV analysis for the 1400 hour video sequence.

### 4.1.3 Analysis at 1700 hours

The water level at 1700 hours was only 0.2 meters, much lower than the other two sequences. Because of this, a slighter distortion of the rectified image occurred.
The same amount of smoothing was done to this file as was to the 0800 sequence and the image colors were also inverted. Similarly, this sequence, being analyzed right around low tide, had slower velocities and was therefore analyzed every other frame. At this time it is possible to see the ground control points and the flow is very circular compared to a strictly in or out flow. An un-rectified and rectified image before analysis is shown below in Figure 10.
Figure 10. Un-rectified (top) and rectified (bottom) image for the 1700 hour video sequence.
Unlike the first two video sequences, this one occurs with a much lower water level and with a very irregular flow. The general shape of the flow here is a clockwise teardrop with plenty of eddies forming. With a couple GCP’s in the field of view and the two landmasses in the corners, it is much easier to get recognize the area being assessed and comprehend the velocity fields in this analysis. Shown in Figure 11 below, velocities are small and don’t get much faster than 0.05m/s in any region. Because of the slower rate of texture change, the directional component of the vectors seems to be more accurate that the previous two time sequences.

Figure 11. Single Frame PIV analysis for the 1700 hour video sequence.
4.2 Vorticity

Vorticity, as described earlier, is a property of fluids that describe the local spinning with respect to a center point and other points near it. This is not, however, the same as angular velocity. Meaning just because a particle follows a curved path, does not mean it has vorticity. It must be moving faster or slower compared to the particles in its immediate area to have the spinning effect that can be seen in eddies. With a tributary like this that has three outlets (or inlets), different speed fluids collide and form eddies with vorticity regularly. Average vorticity can be developed from flow through a short period of time when the movement is relatively constant. The image below shows the first of these vorticity averages for the 0800 hour video sequence both with and without the average velocity vectors. Red represents a positive vorticity, blue a negative, and yellow a zero value.
Figure 12. Average Vorticity field for the 0800 sequence without (top) and with (bottom) average velocity fields.
In Figure 12 above, the red areas represent what would be a clockwise spinning motion. Since the flow is moving to the bottom of the image, this means that the flow to the right of these red spots was moving more quickly than that to the left. This can create the illusion that flow to the left this spot is moving upwards, when in fact it is just moving that much more slowly in the same direction.
Figure 13. Average vorticity field for the 1400 frame video sequence without (top) and with (bottom) average velocity fields.
The vorticity field for the 1400 frame shown in Figure 13 is relatively uneventful. Since the flow was moving towards the top of the image so uniformly, eddies and other fluid nuances did not have the time to develop. The blue bar on the left and red edge to the right are more boundaries of the video frame than actual intensities in the positive or negative values of vorticity.
Figure 14. Average vorticity field without (top) and with (bottom) average velocity for the 1700 hour video sequence.
As stated before when analyzing this PIV sequence, the flow around this entire field of view is generally clockwise once rectified, which is solidified by this figure with a strong positive vorticity in the center of the image. The flow is the strongest at the left and created a red circle as the fluid inside this circle is hardly moving at all. Again, the blue bar on the left edge is more due to the zeros of the PIV analysis and boarder of the image being still than actual vorticity results.

4.3 In–Situ Comparison

While getting good particle image velocimetry data and being able to convert velocity vectors into vorticity was a major component of this research, getting the opportunity to compare gathered results to another instrument that aims to find the same measurements is an opportunity that has to be capitalized on. Although the EMCMs are not visible on the infrared image, Figure 15 shows the general locations of the sensors as well as a relative location due to the rectification of the images as well as their locations on the RGB camera.
Figure 15. EMCM location for C1, C2, and C3 as appears from the camera (top) and as it is shifted for the rectification (bottom).
These values of the along stream velocities were compared to the velocity vectors through PIV and are discussed below. Cross stream values are added in all of the figures to show general shape, but numerical values were too small and fluctuating to compare the PIV with the in-situ data.

4.3.1 Velocity Comparison for 0800

Figure 16. Average Velocity field for 0800 Video Sequence.

Shown in figure 16 above, C1, C2, and C3, had along stream velocity readings of -0.1518m/s, -0.1681m/s, and -0.0314m/s respectively. The average of the entire along stream field, excluding grid points with an average of zero, was -0.0264m/s. Though this value is relatively low, there were many vectors with averages as high in
magnitude as -0.07m/s. It is important to note as well that the EMCM’s are located at the neck of the tributary where the velocity of the water has to increase. Despite the lack of exact layover, the general direction of the flow is absolutely concurrent with that of the sensors

4.3.2 Velocity Comparison for 1400

Figure 17. Average Velocity field for 1400 hour video sequence.

For the 10 minute average at 1400 hours, C1, C2, and C3 had along stream velocity vectors of 0.203m/s, 0.3933m/s, and 0.2505m/s respectively. Again, shown in Figure 17, the region with which the velocity vectors are being made by the PIV program are over a much larger area than the neck of each entrance where the
EMCM’s are located. The full field along stream velocity average is 0.0688 m/s, again eliminating those with an average of zero. With some vectors having averages at and above the 0.2 m/s mark, the flow field using PIV and the in-situ data do align, just not as much as to say that they are equivalent.

4.3.3 Velocity Comparison for 1700

![Average Velocity Field](image)

Figure 18. Average Velocity field for the 1700 hour video sequence.

Figure 18 shows the video sequence with which the PIV and EMCM’s can draw almost no relation, but not for fault of either instrument. C1, C2, and C3, had along stream velocities of 0.38 m/s, -0.105 m/s, and 0.305 m/s respectively. Because of the circular nature of the flow field, it is senseless to extract averages over any sort of
space for this sequence. Additionally, the fact that the field of view of the rectified image doesn’t extend to the actual locations of the EMCM’s its impossible to say that the readings from the in-situ devices are incorrect with respect to the velocity field can be seen here.
Chapter 5

DISCUSSION

5.1 Image Rectification

As was clearly shown in this report, the images through rectifications for flows with higher water depth got substantially skewed. Given the apparent observed angle of the camera with respect to the ground, it seemed like a bit extreme distortion for only a meter change in water depth. That being said, the FLIR infrared camera was much more zoomed in than the RGB and was at a slightly harsher angle to the plane to be rectified upon. Although not ideal for a visual interpretation of the flow field, georectification was a necessary step to get accurate velocity vectors at each stage of the tidal flow.

5.2 PIV and In-Situ Analysis

After some trial and error using a video sequence with a low water depth and many visible GCPs, an appropriate interrogation and search window were decided upon. After that, it was relatively easy to switch between video files and simply change the depth of the water in the code to get different data sets. What came out of PIV analysis were surface velocities that were significantly lower (five or six times in some cases) than that from the EMCMs. However, this does not immediately imply that either the in-situ data or the PIV results are wrong as there are many factors that make the two data sets differ. The main difference is that the EMCMs were located at the bed of the channel flow while the PIV code only detects surface velocities.
Although in most cases given a long standing flow in the same direction renders velocities at the surface greater than that near the bed, other conditions can affect this generality. One of the conditions specific to this study is the location of the EMCMs with respect to the field of view of the infrared camera. The PIV was recorded in the middle of the tributary where the flow is certainly the widest and most open while the in-situ instruments were in the neck of the three channels. This factor would render the EMCMs to have a larger velocity vector as flow increases through smaller channels. A second, less stable possibility for differences in surface and near-bed flow is wind. If a strong wind is heading in the opposite direction of general flow, the surface flow, especially that picked up in textures by the camera, would be significantly dampened. With no wind gauges near the surface of the tributary, it is hard to say whether or not this was a major factor.

5.3 Vorticity

The vorticity of the flow field is hard to show to its full potential without a video sequence. This is because the vorticity of uniform flows (such as the 1400 hour sequence) is rather plain and almost non-existent, while the vorticity of irregular flows is extremely interesting, but when averaged onto one field many of the eddies are not seen. That being said, the vorticity fields can be a good visual check to what one might think is happening in the flow. This was shown best in the 1700 hour average field. The spinning and twisting flow that was seen in raw imagery was confirmed with the PIV sequence and again solidified with the vorticity field.
Chapter 6

CONCLUSION

This study set out to explore two main abilities of PIV. First, to test the effectiveness of particle image velocimetry as a form of fluid motion analysis for a large space throughout time; and second to identify whether or not these values would be comparable to the in-situ instruments that had already been analyzed.

From a visual standpoint, watching the Matlab movie sequences run with the PIV velocity vectors overlaying the rectified video file seemed to give an air of correctness, at least in terms of general flow shape. Although the tide rising caused the image rectifications to take an odd shape, the vectors still managed to flow in a way that seemed quite sensible. Additionally, the average vorticity fields looked just as one would think they should, based on the video files. Again, it is certainly not enough to use mere sight to complete the analysis, but it is a good check to see if things make general sense. The main benefit here with PIV is that velocity fields are being created over a 2-2.5 square meter area, where the EMCM’s are restricted to the single location. Despite the values of the PIV analysis being quite different from the in-situ data, reasons for these changes can be explained. For one, the locations of the instruments (surface for PIV and near-bed for in-situ) will have an impact on this data. Secondly uncertain factors such as the wind make for the conclusion that given a direct comparison, the results should not have the exact same values. Because of the PIV codes ability to pick up small texture differences and follow the direction of flow so well, it seems that is velocity component would not be far from correct. Being able
to make different assumptions, follow eddies, and relate these values to sediment transportation could be invaluable to the furthering of our knowledge in the realm of fluid mechanics.
REFERENCES


