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Optimization of PIV Data from Waves Propagating through Ice Floes

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14. ABSTRACT
This report describes an examination of particle imaging velocimetry (PIV) datasets from a recent wave-ice experiment, in which the quality of the post-processed data is compared and optimized. RMS velocities, vorticities, and selected velocity time series are generated for multiple locations and data collection frequencies using two different post-processing methods. We determine the best post-processing procedure for these datasets, identifying the optimal region for analysis in PIV images and the most effective data smoothing method.

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Wave-ice interactions, PIV, Experiment, Boundary layer, Velocity profiles

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Optimization of PIV Data from Waves Propagating through Ice Floes

Abstract:

A laboratory experiment was conducted at the Cold Regions Research & Engineering Laboratory (CRREL) in late 2021 to measure surface wave propagation through ice floes in a salt-water tank (Orzech et al., 2022). A particle imaging velocimetry (PIV) system was used to measure fluid velocities under the moving ice. The challenging conditions of the experiments - including bubbles near the water-ice boundary, moisture buildup on the cameras, and insufficient or excessive usage of seeding particles - negatively impacted the quality of the PIV data. This report describes an examination of datasets with different sampling frequencies, wave characteristics, and/or ice conditions, in which the quality of the post-processed data is compared and optimized. RMS velocities, vorticities, and selected velocity time series are generated for multiple locations and data collection frequencies using two different post-processing methods. The results are evaluated to determine the best post-processing procedure for these datasets, identifying the optimal region for analysis in the PIV images and the most effective data smoothing method. We demonstrate the deterioration of data quality with decreasing PIV sample rate and increasing distance from the center of the image. These findings will streamline and focus future data analysis for scientists measuring wave propagation through ice floes with PIV in the lab or field.

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1 INTRODUCTION

A laboratory experiment was conducted at the Cold Regions Research & Engineering Laboratory (CRREL) in late 2021 to measure surface wave propagation through ice floes in a salt-water tank (Orzech et al., 2022). A particle imaging velocimetry (PIV) system was used to measure fluid velocities under the moving ice. The challenging conditions of the experiments -including bubbles near the water-ice boundary, moisture buildup on the cameras, and insufficient or excessive usage of seeding particles - negatively impacted the quality of the PIV data.

This report documents an examination of datasets with different sampling frequencies, wave characteristics, and/or ice conditions, in which the quality of the post-processed data is compared and optimized. RMS velocities, vorticities, and selected velocity time series are generated for multiple locations and data collection frequencies using two different post-processing methods. We demonstrate the deterioration of data quality with decreasing PIV sample rate and increasing distance from the center of the image. The results are evaluated to determine the best post-processing procedure for these datasets, identifying the optimal region for analysis in the PIV images and the most effective data smoothing method.

The lab tests were conducted in a 14 m x 2.5 m x 2 m wave basin (*Figure 1*) at CRREL's Frost Effects Research Facility, which was maintained at -7˚C or below for the entire period. A primary goal of the experiment was to capture highly resolved records of the fluid velocity fields and boundary layer that are produced as waves travel through broken ice floes mixed with frazil. To accomplish this, a particle imaging velocimetry (PIV) system was submerged beneath the surface ice, with its laser aimed upward (*Figure 2*). An ice layer was allowed to form on the water surface each night. The PIV system was deployed on an aluminum base plate that was fixed to the tank bottom, with the plate center approximately 150 cm below the water surface. The system consisted of an upward-pointing, solid state, class IV laser paired with a rotating mirror that fanned the beam to create a tri-angular sheet of light, which expanded to approximately 70 cm width the water-ice interface. Two mounted cameras were used to acquire PIV image pairs from the fanned laser region at approximately 330 Hz, tracking the motion of seeding particles in the plane of the beam to determine fluid velocities in three dimensions.

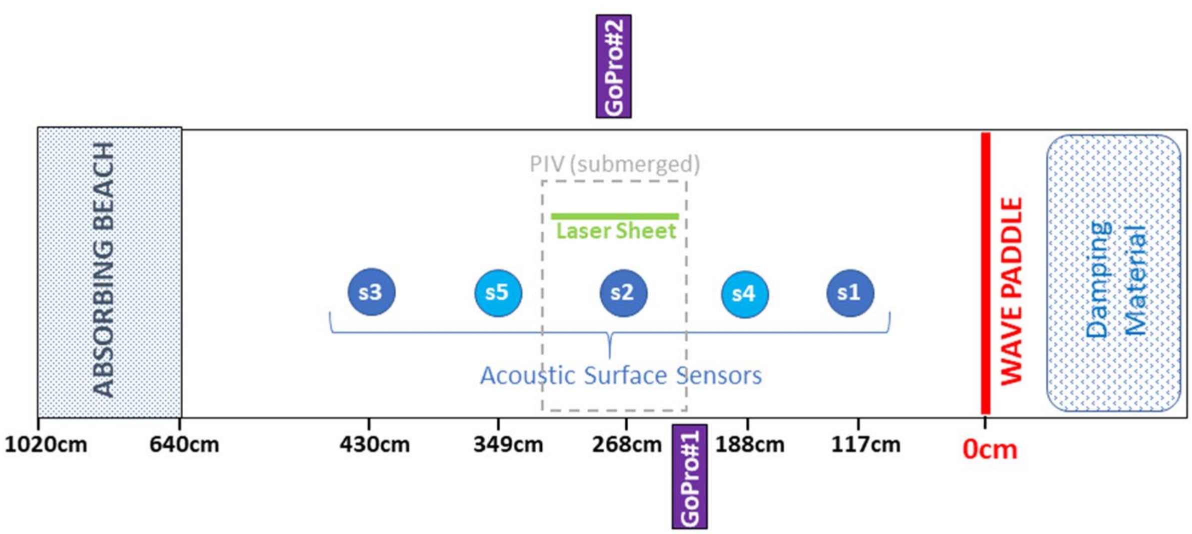

Figure 1. Instrument Layout for CRREL Facility Experiment

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Using specialized software from LaVision Inc., the PIV data (*Figure 4*) were post-processed to extract velocity fields by identifying individual seeding particles and measuring their motion between pairs of images (*Figure 5*). Velocities were extracted from the images using several different "increments" (or sampling frequencies). Increment values ranged from 1 to 32, corresponding to sampling frequencies ranging from 330 Hz down to roughly 10 Hz, respectively. Thus, for example, with an increment of 8 (frequency of about 41 Hz), velocities were determined by comparing every eighth image in a PIV data set.

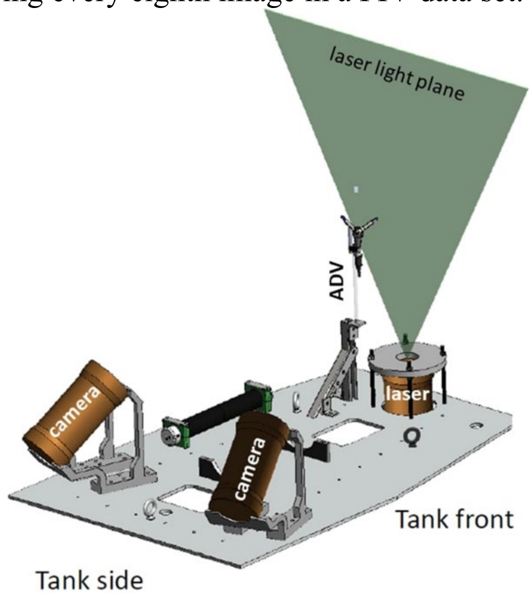

Figure 2. Diagram of PIV System

The analyses described in this report were performed using selections from these velocity data files, which were only available from 5 of the experiment's 64 trials (i.e., trials 2, 11, 18, 22, and 25). Under the supervision of the lead author (MO), the co-author (KP) developed and adapted a series of programs within the MATLAB environment to examine and compare the data sets, extracting RMS and mean velocities, computing localized and averaged vorticities, and using Fourier transforms to produce low- and high-pass filtered time series at selected locations.

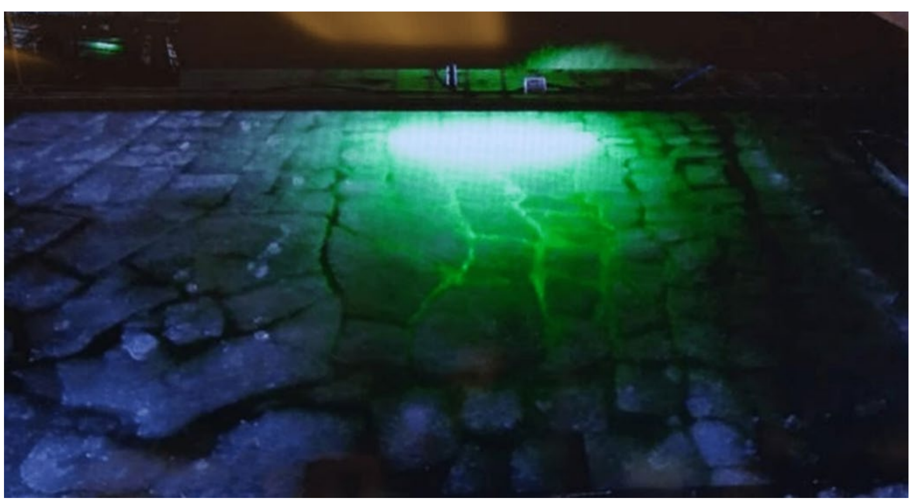

Figure 3. Picture of ice surface during a PIV measurement.

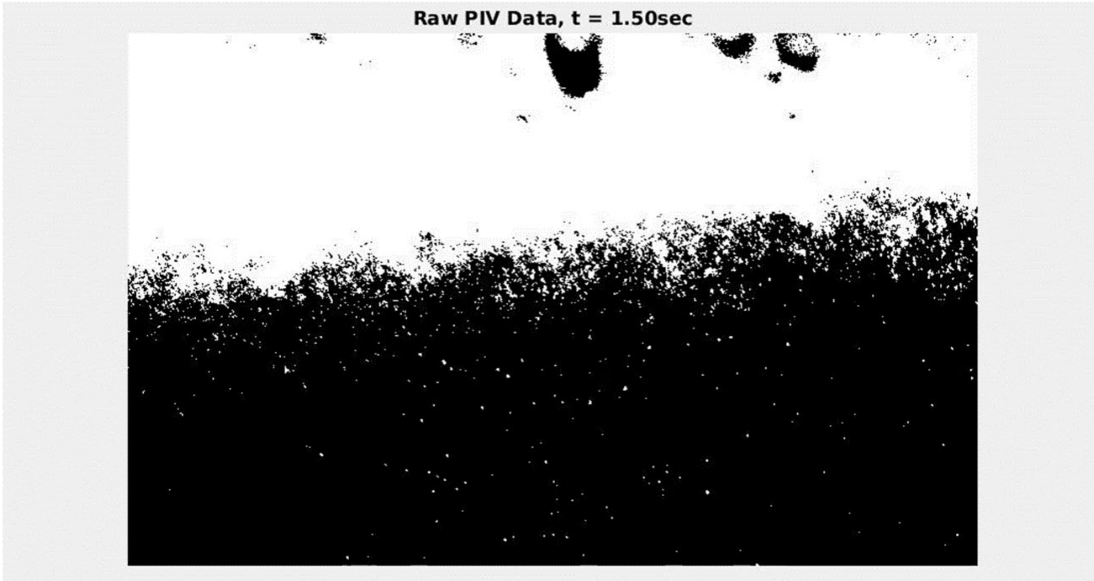

Figure 4. Section of single image showing raw PIV data. Cloudy white region along top of image is surface ice. Small white dots below the ice are mostly seeding particles, whose positions were tracked to measure the velocity field (see Figure 5 below).

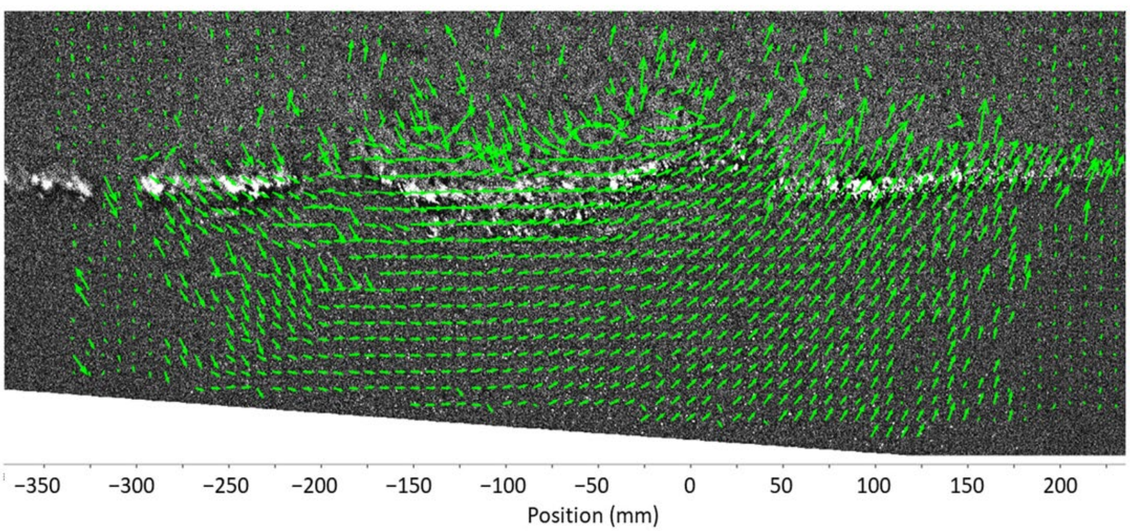

Figure 5. Sample PIV velocity data, estimated from displacements between consecutive (or nearly consecutive) individual images.

2 DATA ANALYSIS FREQUENCY/INCREMENT SIZE

A lower data processing frequency (i.e., larger increment between compared PIV images) used during the computation of velocity fields can reduce the storage space and computing time necessary to analyze large PIV data sets. Ideally, however, this frequency must be large enough to properly capture the magnitudes and directions of the velocities at the scale of interest. Thus, for analyzing mean flows, the PIV image sampling frequency can normally be lower (e.g., O(10

Hz)), but analyzing more rapidly varying turbulent oscillations requires this frequency to be much higher (e.g., O(100 Hz)).

A primary goal of this summer internship was to find the ideal data processing frequency to use for future analysis of RMS velocities, vorticities, and velocity time series generated by waves under ice floes. To accomplish this, we plotted these parameters for a range of different collection frequencies and compared the plots to find the lowest frequency (highest increment) that does not experience a significant reduction in quality compared to the highest processing frequency (i.e., 330 Hz, or increment 1). Through an initial process of plotting and comparing RMS velocities for all available data sets, we were able to determine that frequencies at or below 41 Hz generally resulted in output that was significantly degraded in comparison with the lowest increment size. To further home in on the optimal sampling frequency, we compared data sets for frequencies 41 Hz and 82 Hz extensively.

Color plots of RMS along-tank (U_{RMS}) velocity from Trial 18 are shown at all locations for sampling frequencies 82 Hz and 41 Hz in

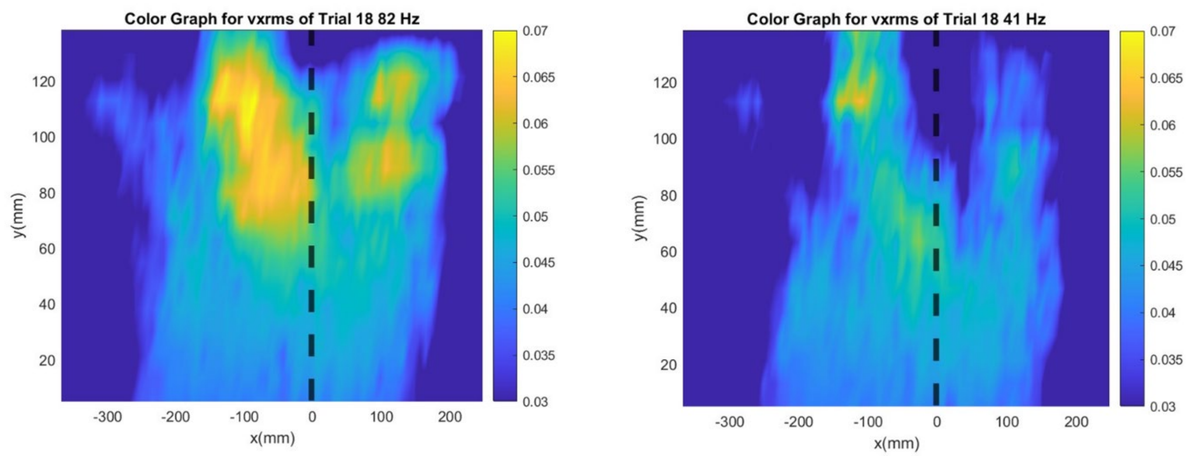

Figure 6, left and right panels, respectively. These plots suggest that 82 Hz is probably the better PIV processing frequency, as the image of the 82 Hz data consistently shows the higher RMS velocities that are expected near the water-ice interface at all horizontal locations, while the results for the 41 Hz data exhibit a large dip in near-surface RMS velocity at locations near x = 0 (likely due to erroneous velocity estimates at this sampling rate).

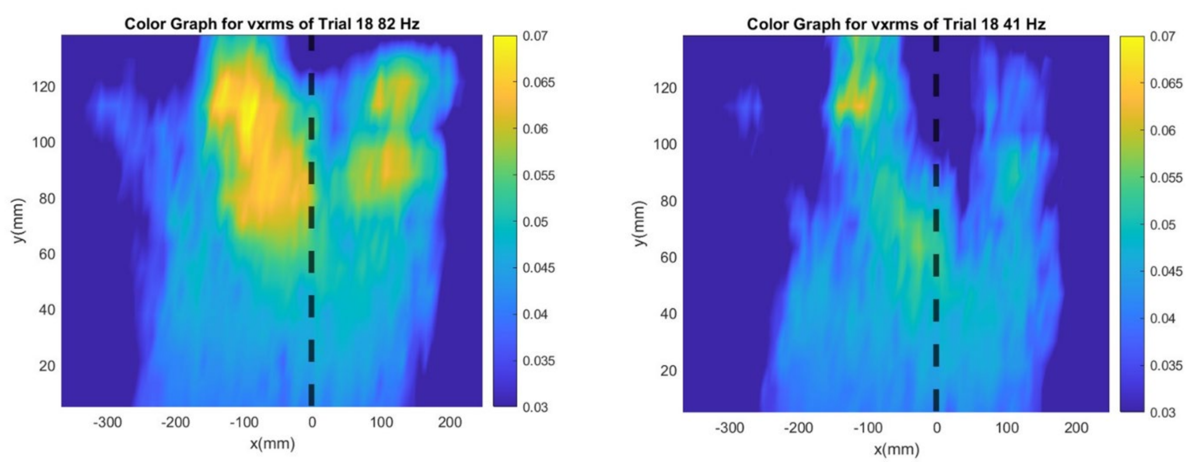

Figure 6. RMS along-tank velocities for full PIV image region, recorded during Trial 18. Left panel: Images processed at sampling frequency 82 Hz. Right panel: Images processed at 41 Hz.

The profile plots of RMS velocity corresponding to these color graphs are displayed in *Figure 7* below. These panels illustrate how the erroneous dip seen in right panel of

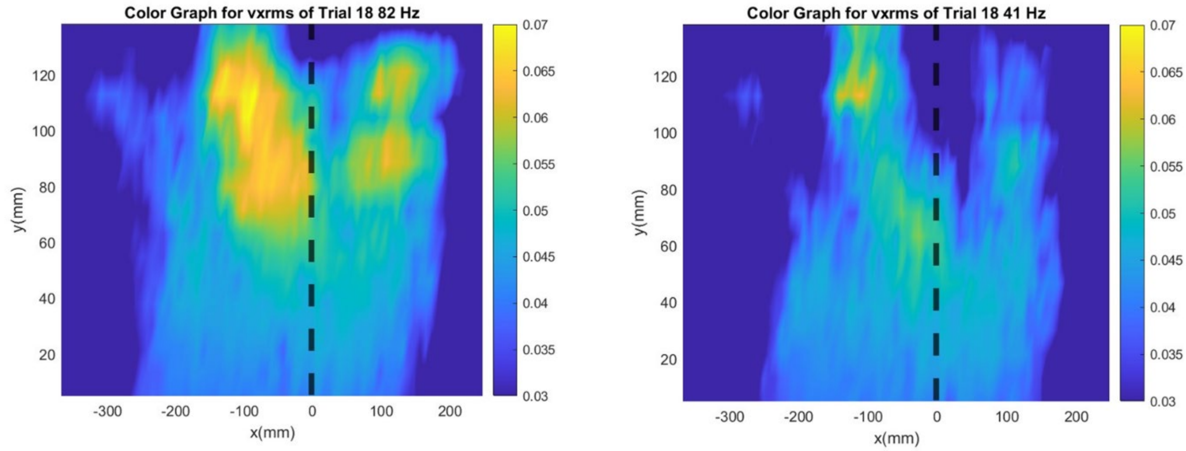

Figure 6 interferes with the measurement of the velocity boundary layer near the water-ice interface (light gray line at y = 100 mm in *Figure 7*). The existence of this boundary layer is visible in the divergence of the U_{RMS} profile from the dashed open-water profile line in both panels of *Figure 7*. However, with the 82 Hz data (left panel), the layer extends up to 90 mm on the vertical axis (above which it is disrupted by interference from the surface ice). In contrast, for the 41 Hz data (right panel) this layer only extends up to about 70 mm (with locations closer to the surface obscured by processing errors).

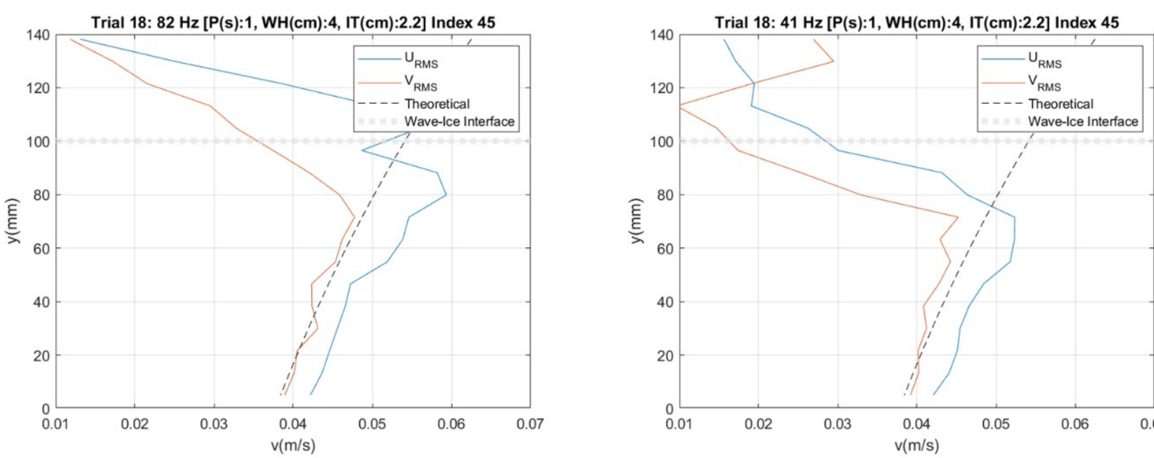

Figure 7. Profile plots of RMS along-tank (U_{RMS}) and vertical (V_{RMS}) velocity, as recorded during Trial 18. Left/right panels correspond to those of

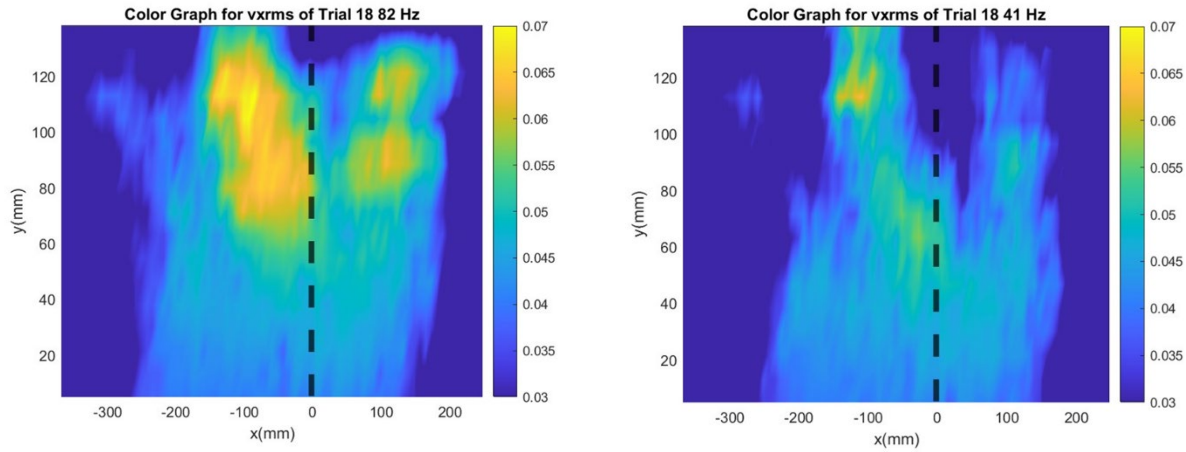

Figure 6 above and were obtained for the x=0 location in each panel of that figure. Left panel: From velocities processed at sampling frequency of 82 Hz. Right panel: From velocities processed at 41 Hz.

Time series from a single selected location (45, 10) in Trial 12, frequencies 82 Hz and 41 Hz, are shown in *Figure 8*. The blue line shows the original, unfiltered time series, while the black line indicates the time series after a low-pass frequency Fourier Transform has been applied (removing all components with frequency above 4 Hz). When compared to the plots of filtered 41 Hz data, the time series for filtered 82 Hz data is much smoother. The original, unfiltered 82 Hz data also contains fewer drops to zero, which result from inaccuracies in data collection and processing. This is the pattern we found among most data sets: 82 Hz data is the lowest frequency without major changes in the quality of plots and accuracy of bulk parameters calculated from the data.

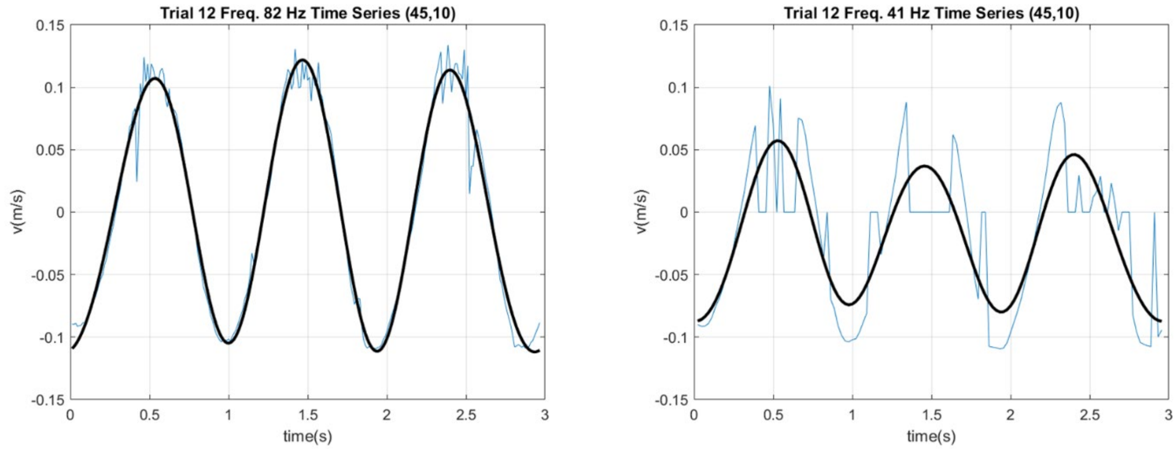

Figure 8. Time series of horizontal velocity recorded at a single point (45, 10) in the PIV image series for Test 18. Left and right panels correspond to those in

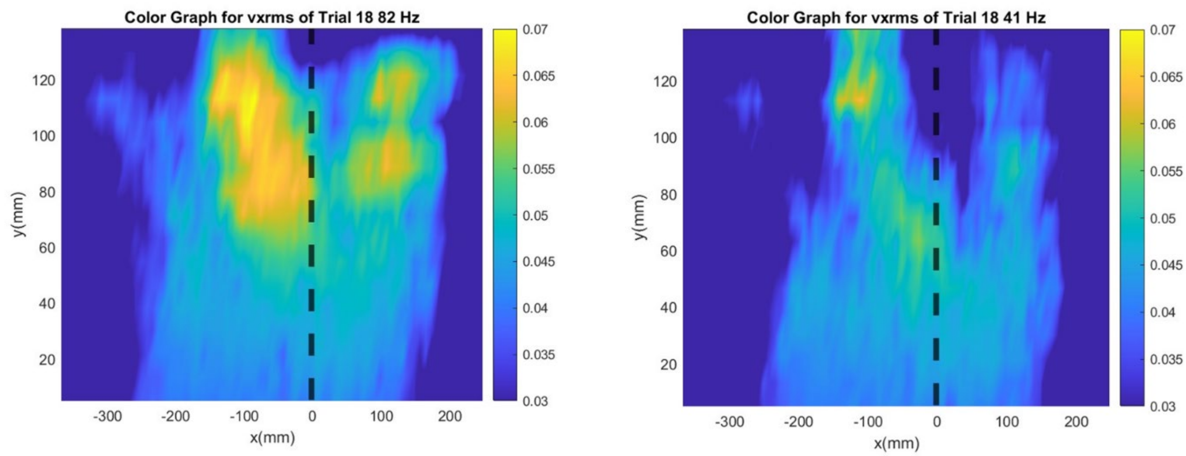

Figure 6, respectively, and location corresponds approximately to x=0m, y=100mm in that figure. Light blue line in each panel is original time series of estimated velocity (including measurement noise). Dark black lines correspond to low-pass-filtered velocity, as described in the text.

3 OPTIMAL ANALYSIS LOCATION

We found that the quality of the PIV image data tended to be highest near the horizontal center of the laser light plane and deteriorate as one moved away in either direction. An example of this deterioration is shown in *Figure 9*, which compares vertical profiles of average velocity magnitude, $\left|\overline{u}\right| = \overline{\sqrt{u^2 + v^2}}$.

The plots in *Figure 9* were generated using data from Trial 13 with a sampling frequency of 41 Hz. All three profile panels were plotted in the same manner but used data from different horizontal locations (indices) in the data set. These plots illustrate how average velocity magnitude profiles that are computed near the left and right sides of a PIV data set (image alongshore indices 20 and 60) are not very smooth and the peak average velocity magnitude is not as well-defined.

In contrast, the profile near the middle of the data set (index 45), which is at location x=0 in the PIV image frame, is much smoother and the peak average velocity magnitude can be seen clearly. Following an analysis of these plots and multiple similar plots from data sets in different trials, we conclude that the optimal location range to analyze PIV data is most often in close proximity to the center of the laser light plane.

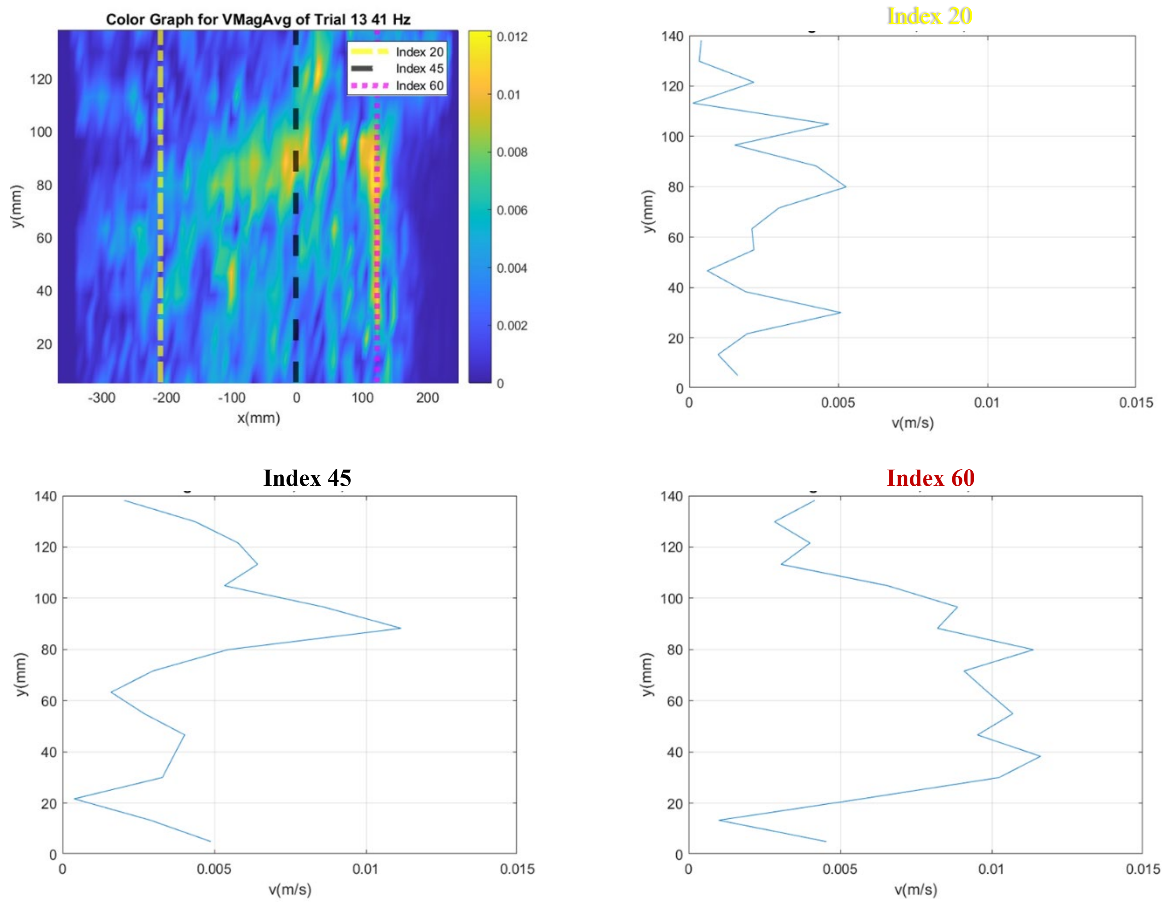

Figure 9. Profiles of average velocity magnitude at three along-tank locations.

4 SMOOTHING/FILTERING TECHNIQUE

The raw PIV data has errors and noise throughout all of the data, and this can be clearly seen with data near the surface and ice boundary layer. The plot in *Figure 10* below shows samples of theoretical along-tank RMS velocity profiles near the wave-ice interface, computed by representing the ice as a viscous layer (Yu et al., 2022). The three panels in *Figure 11* on the next page present measured along-tank RMS velocity profiles obtained from 330 Hz time series data for a central transect of trial 18, using three different filtering methods.

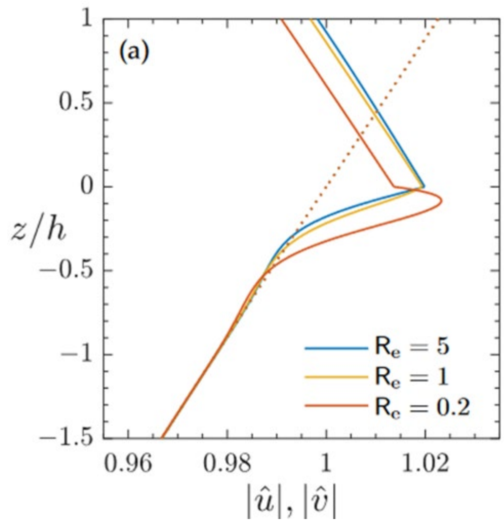

Figure 10. Theoretical profiles of normalized along-tank (colored) and vertical (dotted) velocity magnitude for waves under a viscous surface layer, plotted versus depth (normalized by ice layer thickness, h), for several different flow configurations given by Reynolds number R_e (from Yu et al., 2022).

In *Figure 11*, the unfiltered profile (top left) was computed from the original PIV velocity time series including noise and errors, and it deviates considerably from the theoretical profiles of *Figure 10* in the region near the ice. The smoothed profile (top right) first averages the raw velocity time series using a 10-point running average before computing RMS velocities but still does not produce a better fit to theory than the unfiltered plot. The low-pass Fourier Transform (bottom panel) removed all higher frequency signals in the data, keeping only velocity components with frequencies of 4 Hz and below. This method effectively eliminated both noise and error signals from the velocity profile near the ice, producing a profile that much better represents the boundary layer features shown on the theoretical RMS plot. Therefore, we concluded that the best method of post-processing the data was to use a low-pass Fourier transform in order to efficiently analyze wave-ice interactions.

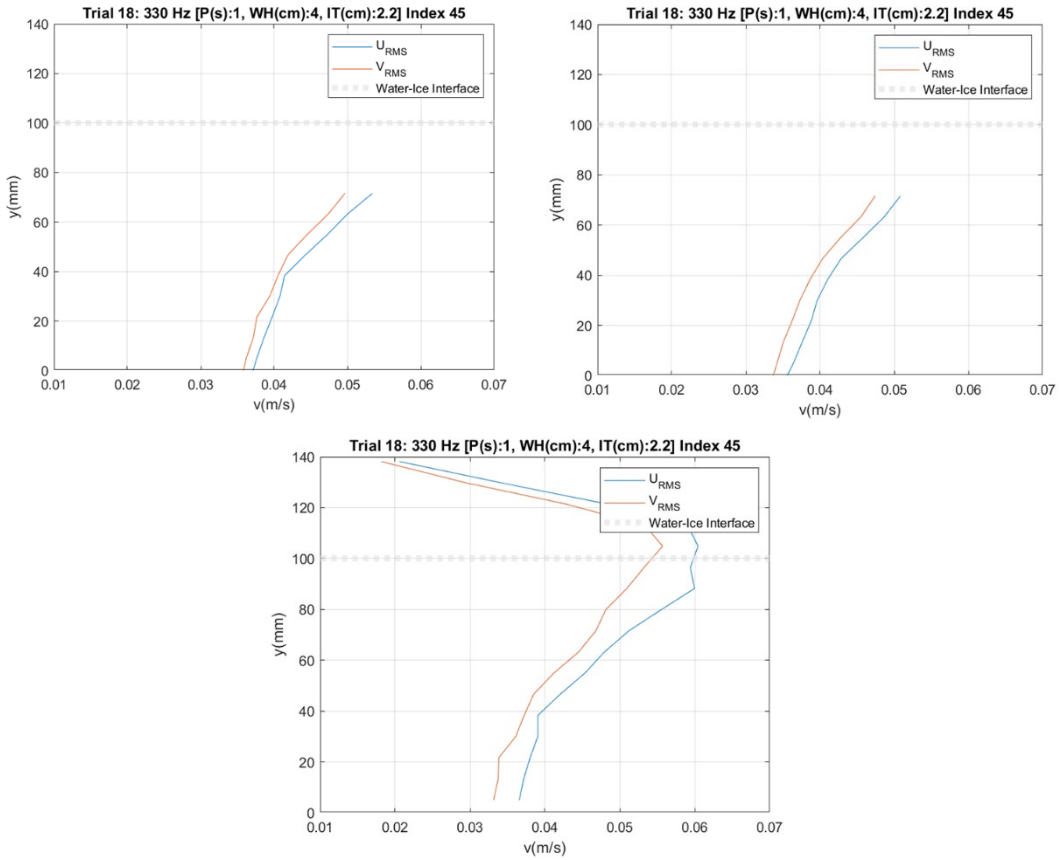

Figure 11. Profiles of RMS velocity computed using velocity time series from three different processing techniques: unfiltered (top left); 10-point smoothed (top right); and low-pass FFT filtered (bottom).

5 MAJOR FINDINGS

- ❖ There are many errors, inaccuracies, and problems experienced with PIV experimentation, but many of the problems can be resolved with the correct post-processing methodology.
- ❖ The central location of the laser light plane and other locations in the vicinity of it are the best locations to obtain PIV data for further analysis.
- ❖ The optimal data analysis frequency to use for RMS velocity plots, time series, and other measurements in this experiment is 82 Hz. Higher frequencies can be used for analysis of specific areas in the PIV system or for utmost accuracy, but these will be less efficient.
- ❖ In comparison to 82 Hz plots, lower frequencies experience a major loss in quality of data as indicated by RMS velocity color graphs and time series.
- ❖ Low-pass Fourier Transform filters are the best smoothing/filtering technique as the plots generated with this method most closely resemble theoretical estimates when compared to standard running average smoothing methods.

6 WHAT'S NEXT?

We are continuing to process the extensive PIV dataset from this first and second experiments, identifying tests with data of acceptable quality and excluding those with excessive anomalies. The optimization techniques mentioned in this poster will be applied when plotting new data. When the automated identification and marking of the surface ice is finalized, we will use this to apply a surface-following analysis to the boundary layer. This should provide a better-resolved picture of RMS velocity very close to the interface, producing a measured velocity profile that more closely resembles the theoretical results.

7 REFERENCES

Orzech, M.; Yu, J.; Wang, D.; Landry, B.; Zuniga-Zamalloa, C.; Braithwaite, E.; Trubac, K.; Gray, C. (2022). Laboratory measurements of surface wave propagation through ice floes in salt water. J. Mar. Sci. Eng., 10, doi.org/10.3390/jmse10101483

Yu, J.; Rogers, W.E.; Wang, D.W. (2022). A new method for parameterization of wave dissipation by sea ice. Cold Reg. Sci. & Tech., 199, doi.org/10.1016/j.coldregions.2022.103582.