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Linking Surface Turbulence with Riverine and Coastal Geometric and Bathymetric Variability

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14. ABSTRACT

Infrared (IR) imagery has proven to be a powerful tool for remotely observing and characterizing a range of riverine and coastal processes, including breaking waves [1], coherent flow structures [2] and surface currents [3]. Previous efforts have utilized infrared imagery to characterize the surface flows of a spatial area of interest over a brief snapshot in time. The primary objective of this study is to quantify the variation in surface flow and turbulence due to spatial variations in river geometry and temporal changes in bathymetry over seasonal time scales. To achieve our objective, we developed and successfully deployed a novel, long-term monitoring station that is capable of observing the thermal signature of the water surface over seasonal time periods. The study included two stations with one deployed in a riverine environment and one deployed in a coastal environment. In latter case, seasonal-scale changes in bathymetry have a significant impact on nearshore hydrodynamics. Both stations demonstrate a significant advancement in the use of IR imaging to observe hydrodynamic processes in a range of environments over long time scales.

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LINKING SURFACE TURBULENCE WITH RIVERINE AND COASTAL GEOMETRIC AND BATHYMETRIC VARIABILITY

1. MOTIVATION & SIGNIFICANCE

Infrared (IR) imagery has proven to be a powerful tool for remotely observing and characterizing a range of riverine and coastal processes, including breaking waves [1], coherent flow structures [2] and surface currents [3]. Previous efforts have utilized infrared imagery to characterize the surface flows of a spatial area of interest over a brief snapshot in time. The primary objective of this study is to quantify the variation in surface flow and turbulence due to spatial variations in river geometry and temporal changes in bathymetry over seasonal time scales. To achieve our objective, we developed and successfully deployed a novel, long-term monitoring station that is capable of observing the thermal signature of the water surface over seasonal time periods. The study included two stations with one deployed in a riverine environment and one deployed in a coastal environment. In latter case, seasonal-scale changes in bathymetry have a significant impact on nearshore hydrodynamics. Both stations demonstrate a significant advancement in the use of IR imaging to observe hydrodynamic processes in a range of environments over long time scales.

2. TECHNICAL APPROACH

We have designed and developed a next-generation, long-term monitoring station that autonomously captures IR imagery at up to 60 Hz. The camera features a long-wave infrared sensor with a thermal resolution of <40 mK and captures a 50° field-of-view. The system is controlled by a small form factor computer and can be remotely accessed through a cellular modem. A fully ruggedized and air-conditioned enclosure makes this system capable of withstanding harsh conditions and is adaptable to a range of coastal and riverine environments. IR image processing algorithms have been developed and refined, allowing for on-board processing of image streams. Both systems have collected thermal imagery in 10 minute bursts each hour, 24 hours per day, throughout much of 2020.

The first monitoring station was constructed and deployed on the Pearl River at Stennis Space Center, MS during the fall of 2019. Mounted on a fixed platform, the system captures approximately a 30 m reach of the river with an average pixel resolution of 10 cm. Imagery from the fixed station along with supplementary imagery collected from an unmanned aircraft system (UAS) were used to estimate spatial variability of surface currents through use of a spectral method.

A second version of our monitoring station design was developed in collaboration with the USACE ERDC and was deployed in the winter of 2019 at the Field Research Facility (FRF) in Duck, NC. The second station, mounted on a fixed tower, captures infrared imagery of a 300 x 500 m region of surf zone with an average pixel resolution of 40 cm. Using similar signal processing methods, imagery from the second station has been used to quantify longshore currents, wave runup, and bathymetry. Additionally, an open-source MATLAB application, the Coastal Imaging Station Design Toolbox, was developed to aid in imaging station design and data collection planning [4].

Manuscript approved February 12, 2021.

3. RESULTS

3.1 Riverine IR Imaging Station

Turbulent coherent structures in the natural environment generate temperature variability on the water surface that can be clearly observed in collected infrared imagery. Several techniques that are typically applied to optical imagery have been adapted to analyze the observed temporal and spatial changes in thermal signature and used to estimate surface flow characteristics. Using a technique that computes the velocity spectrum from observed pixel intensity [5], mean surface currents have been estimated across the field of view of the camera. The method is demonstrated in Figure 1 using supplementary imagery collected by UAS. Results show that the magnitude of downstream surface currents have significant spatial variability in both the cross-stream and downstream direction. The velocity magnitude patterns have also been seen to vary significantly in time as river stage and discharge fluctuate.

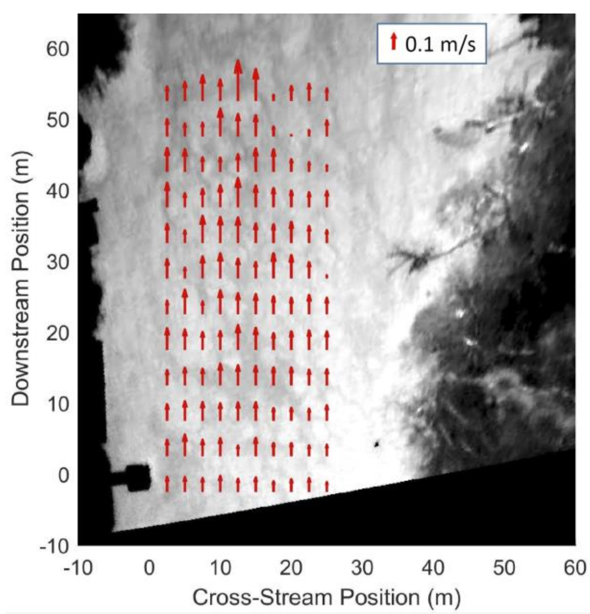

Figure 1: Estimates of downstream surface currents, computed using a spectral method (red), are overlaid on a georectified IR snapshot.

Spatial distribution of surface currents are automatically generated in a through-the-sensor fashion for 10 minutes of imagery collected every hour, 24 hours per day. Additionally, PIV algorithms have been successfully used to visualize surface flow patterns, and feature tracking algorithms have been tested to track the formation and propagation of turbulent structures on the water surface. While image processing routines and algorithms have been successfully refined, in-situ instrumentation to accurately validate surface current magnitudes and turbulent flow patterns, along with regular hydrographic surveys to quantify the influence of temporal bathymetric variability, is still needed; these items remain for future work.

3.2 Coastal IR Imaging Station

The coastal station at the USACE FRF has collected thermal imagery in a similar manner to the riverine station throughout 2020. Adapting techniques developed for optical imagery, we have shown that IR can be used to observe and estimate longshore currents, wave period, wave runup and bathymetry.

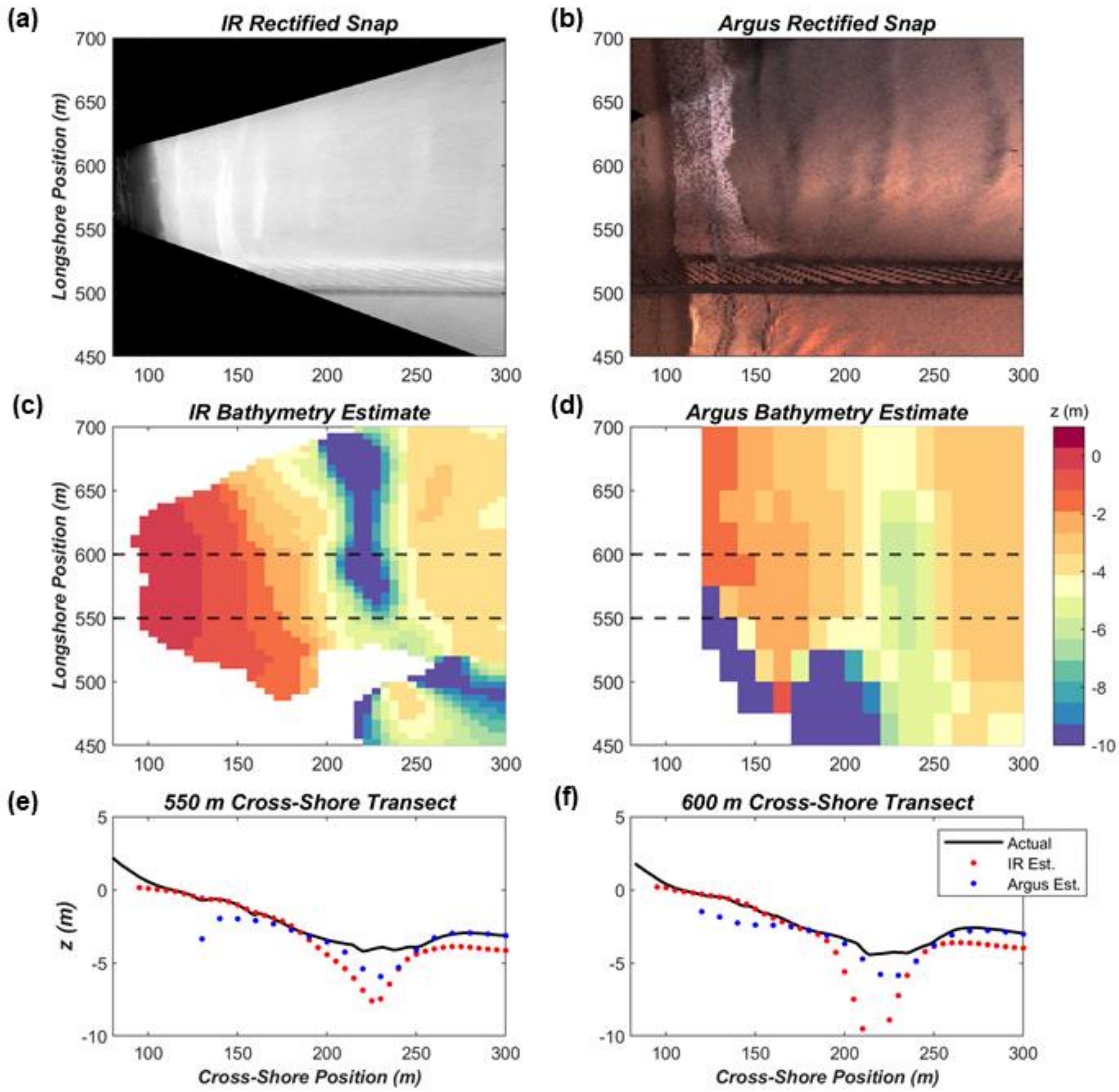

Figure 2: A comparison of estimated bathymetry using the cBathy algorithm is made between coincident IR (a) and (b) Argus georectified optical imagery. cBathy derived bathymetry shows significantly higher resolution for the (c) IR station than the (b) Argus station and a noticeable trench or deep region at approximately 225 m offshore for both systems. Depth profiles for each system are compared to vessel-based hydrographic survey data collected the same day at (e) 550 m and (f) 600 m cross-shore transect in the local FRF coordinate system.

Imagery collected with our IR station can be directly compared with a collocated Argus coastal monitoring station [6] that relies on traditional optical imagery. Data products generated by the Argus station have been highly studied and validated, particularly for use with the cBathy linear depth inversion algorithm [7, 8]. The cBathy algorithm uses spectral analysis of collected surf zone imagery to compute the celerity of intermediate and shallow water waves, solving the linear dispersion relation to estimate water depth. We have adapted this algorithm for use with our station, the first known use of cBathy with thermal imagery.

A comparison of coincident time series demonstrates the capability of IR for use in estimating nearshore bathymetry. Figure 2 shows estimated water depth derived from the cBathy algorithm using imagery collected from each station over the same 20-minute time window. Our IR station has a single, high-resolution camera, whereas the Argus station uses an array of cameras and merges images together to create a comparatively low-resolution orthomosaic image that covers a greater longshore distance. In this example, both IR and Argus-based cBathy results show a synthetic trough at approximately 225 m offshore which agrees with the location of wave breaking during the dataset. High error in depth estimates at the breakpoint is a known weakness of the cBathy algorithm that can be mitigated through time-average filtering [8]. For the purpose of this comparison, no temporal averaging was used.

Transects at 550 m and 600 m cross-shore positions show relative agreement between the two depth estimates and are compared to a vessel-based hydrographic survey collected two hours prior to the image collection. IR derived depth estimates show a high level of accuracy inside the breakpoint as compared to Argus derived estimates, while Argus estimates seem to perform better at the sandbar and farther offshore (increasing cross-shore position in Figure 2). Preliminary results are encouraging for the potential of thermal signals to estimate nearshore bathymetry and hydrodynamic conditions, possibly even out-performing commonly used optical signals in some situations, most obviously at night. A detailed analysis of cBathy performance and error analysis using infrared imagery is ongoing, in preparation for a peer-reviewed publication.

4. FUTURE WORK

Imagery collected by the riverine station has been used to quantify surface currents and demonstrate variation in flow and turbulence on spatial and temporal scales. Preliminary results from PIV and feature tracking algorithms also show promise for quantification of mean and turbulent flow properties. Supplementary and validation data are needed to further investigate and refine these processing techniques. A suite of instrumentation is proposed that would combine IR imaging of the river surface with repeated sonar imaging of the bed, georeferenced surface drifters, in-situ acoustic current profile measurements, and imagery collected via UAS over extended reaches of river. The multi-modal approach will provide critical validation data and couple the surface expression of turbulence observed in the collected image data and the evolving river bathymetry.

Results generated by the coastal station have been used to quantify a range of coastal processes. Direct comparison of accepted optical imagery-based data products with IR-derived products is ongoing. The FRF provides a wealth of data resources that can be used to further validate remotely sensed results including regular hydrographic surveys, acoustic current measurements, LiDAR scans, and GPS enabled surface drifters. The FRF field site provides a unique opportunity to effectively examine and provide new insights into thermal signals present in a nearshore environment.

The existing monitoring station design has potential for improvement. Increasing the number of cameras in the system would significantly expand the spatial coverage of the imagery and is an obvious first step in increasing its observational value. Alternatively, an IR sensor synchronized and assimilated with other remote sensing tools like optical imagery, LiDAR or radar could provide new techniques for characterization of natural environments.

5. NAVAL RELEVANCE

Reliable remote sensing of riverine and coastal environments is crucial to intelligence, surveillance, and reconnaissance (ISR) in support of Naval Special Warfare. Riverine and coastal areas characterized by turbulent mixing over dynamic bathymetry ubiquitously represent operational environments. Infrared imagery may be a powerful tool for environmental monitoring and situational awareness and is not limited to daylight conditions, a significant advantage over traditional optical imaging techniques. The technology developed here under the Karles Fellowship Program represents a powerful step towards adapting existing optical imaging techniques for use with IR imagery and furthering IR capabilities.

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