Characterization of the Riverine Environment through Passive Remote Sensing

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Award Number: N00014-13-C-0387
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LONG-TERM GOALS

The long term goal of the proposed work is to transition an airborne passive remote sensing system to help the Navy and its mission partners to characterize surface water transport and battlespace environments more efficiently and safely.

OBJECTIVES

The objectives of this effort are: (1) understand the physical processes acting above and below the air-water interface in rivers that drive the coherent structures in the thermal skin observed in the infrared imagery; (2) develop the capability to use airborne time-series infrared imagery to derive surface currents in rivers and estuaries; and (3) use this emerging capability to explore river hydrodynamics.

APPROACH

A development objective of the DARPA Infrared Riverine Intelligence System (IRIS) was to retrieve water currents from an airborne mid-wave infrared sensor and to successfully transition this capability to agencies supporting the operating forces. The signal of interest is coherent skin temperature modulations on the water surface that advect downstream. The reliability of the skin temperature signal and its dependence upon a range of environmental conditions and development of data collection guidance were of direct interest to the IRIS program.

The thermal skin is a small (~0.2º Celsius) mean temperature difference between the water surface and the interior water column. The thermal skin is thin (O(1 mm)) and is maintained most of the time due to the flux of heat between the water and the atmosphere. The thermal skin layer in channel flows such as rivers and estuaries has been modeled by [1] and observed by [2,3,4,5,6]. Features in the water column such as surface gravity waves, internal gravity waves, whitecaps, secondary flows and turbulence strain the surface layer and generate coherent surface temperature modulations.

Boils are an example of subsurface turbulence that can disturb the skin layer by their extreme current divergence [7]. Boils act for a short time to remove the thermal layer entirely so that the surface temperature approaches the subsurface bulk water temperature [8, 9, 10]. These boils have spatial scales comparable to the water depth [11], and can be meters or larger in horizontal scale. In addition to strong disturbances from boils, surface layer straining can be caused by flows and turbulence often associated with secondary flows in the channel caused by bends [12,13,14], vegetation beds [15] and bottom roughness variations [16], bathymetry variations [17], or confluences [18,19]. The surface skin layer is strained by these flows on horizontal scales of meters or larger, creating long-lasting surface temperature signals [20,21].

It is these moderate- to larger-scale variations in surface temperature that we set out to detect and track with the aircraft camera system. Other investigators [3,4,5,22,23] have examined small sections of rivers and estuaries from a boat or river bank and found temperature variations that they can detect and track remotely over a long enough period of time to estimate the current. We set out to adapt this technique to an airborne imaging system to derive currents across long stretches of rivers and estuaries.

The thermal signal required for current retrievals is expected to depend upon external environmental factors including the net surface heat flux and river morphology. However, one expects a net surface heat flux and hydrodynamic-driven spatial-temporal variations to be common in rivers. In addition, the assumption that the thermal variations are advected at the local mean surface vector enables measurement of the currents. Our experience on a variety of rivers under a variety of environmental conditions bears this out.

During the DARPA IRIS program, two airborne IR imaging systems were deployed on a Twin Otter: the Airborne Remote Optical Spotlight System – Infrared (AROSS-IR) and Fixed-IR/EO (AROSS-F). In addition, a Cliff-based InfraRed Imaging System (CIRIS) was installed at the top of the Palisades overlooking the Hudson River and a piling instrumented with an air-sea flux package, CTDs and current meters was deployed within the camera field of view. This combined system collected data for two 10-day periods. The AROSS-IR and CIRIS both incorporated a large-format (1 megapixel) mid-wave infrared (MWIR) camera and a large-format (11 megapixel) EO panchromatic camera. The AROSS-F is composed of two large-format MWIR cameras and two large-format EO panchromatic cameras, but fixed to the aircraft instead of positioner mounted like all other AROSS systems.

A series of four Riverine Dynamics Experiments (RIDE 1-4) were carried out during IRIS to collect data for use in algorithm development and validation, and to explore the underlying dynamics controlling skin-temperature modulations.The various test sites were chosen to provide a variety of environmental conditions as well as leverage available data from other researchers and government agencies. The test sites included locations in New York, Connecticut, Pennsylvania, Delaware, Virginia, Maryland, North Carolina, Georgia, Ohio, Idaho, Colorado, Utah, Wyoming, Oregon and Washington.

WORK COMPLETED

In the previous year, we have completed post-processing and quality control from the RIDE #4 (September 2011) data collection. The data products include surface current vectors on 32 m grids over the reaches we sampled. This includes data from the Columbia River, Snake River, Blue River and Colorado River. The data is now available to other investigators (including ONR, USGS and NRL) in support of their ongoing research. We documented the current measurement methodology, comparison to ground truth and example retrievals from various rivers (see Dugan et al 2014). We began analysis of the spatial characteristics of imagery observed on the Hudson river at the Palisades.

This past year, we collaborated with Chris Zappa and Sophia Bremer (LDEO) on analysis of data collected on the Hudson River in 2010. This study focused on connecting boat imagery of the thermal skin with subsurface turbulence and water depths. We found that skin temperature length scales are linearly correlated with depth and surface and subsurface dissipation rates and currents are highly correlated.

We are also investigating the relationship between the temperature modulations in the infrared imagery from the top of the cliff that are associated with coherent features advecting with the mean flow and the environmental parameters measured from our in situ instruments. The infrared imagery from these experiments show a diverse range of temperature modulation patterns, on scales of 20cm to several tens of meters, often masked by the presence of surface waves (See Figure 1). At the low-grazing angle (11° to 27°) of the cliff-top camera, the IR images from the water surface reflect a combination of emitted radiance from temperature modulation on the surface and reflected radiance from the sky above.

In May 2014, Areté installed a Pushbroom Imaging Lidar for Littoral Surveillance (PILLS) and a FLIR SC8000 MWIR imaging system sampling at 2 Hz in a small twin-engine aircraft. Data was collected over the lower Colorado River between Picacho Park and Parker. PILLS is a compact bathymetric lidar based on streak-tube sensor technology. It provides channel and bank topography and water surface elevation at 1 meter horizontal scales and 25 cm vertical accuracy. Surface currents are derived from the MWIR imagery using the IRIS methodology with spatial resolutions down to 5 m with accuracy better than 10 cm/s.

RESULTS

(1) (2)

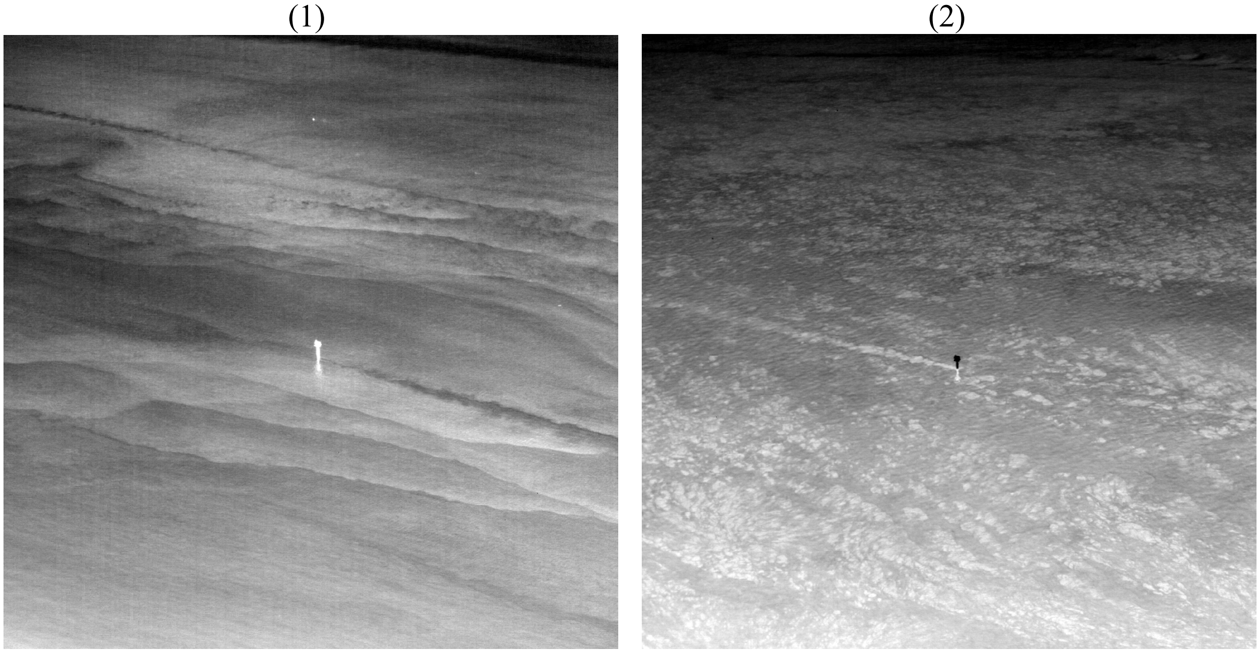

Figure 1: Example IR images taken from the top of the Palisades.
These two images show examples of the complicated and ever changing structures observed in the skin temperature. The instrumented piling is shown in the center of the scene. Image (1) is daytime and ebb tide and image (2) is night time with flood tide. A thermal wake from the piling is observed in both images.

The time-series imagery from the top of Palisades of the Hudson River reveals a continuously evolving scene. Figure 1 shows just two images from this location and a piling is observed in the field of view. Attached to the piling, above and below the water surface, an array of instruments were installed to measure heat flux, wind speed, air and water temperature, current velocity, humidity, radiance, and conductivity.

To separate out the emitted signal due to the temperature modulations and the reflected signal which is modulated by surface waves, we employ a Fourier space filtering technique to exclude the variance in the imagery due to the surface waves. We find the remaining emitted signal to be strongly correlated with wind speed and the air-water temperature difference, and weakly or uncorrelated with stratification and mean current speed. The observed relation between the amplitude of the temperature modulations with wind speed and air-water temperature differences is shown in Figure 2. The largest temperature modulations are observed when the air-water temperature difference is large but the wind speed is low. This is because the heat flux supporting the thermal skin is large but the wind-driven turbulence is small. Increasing wind speed may increase the surface heat flux, but will also increase the turbulence which will act to disturb the thermal skin.

The fused airborne data captures current and depth variability on scales of meters over 10's of kilometers collected in just a few minutes. Figure 3 is an example of surface current and bathymetry retrievals from the Lower Colorado River. Combining data from airborne lidar and infrared imagery,

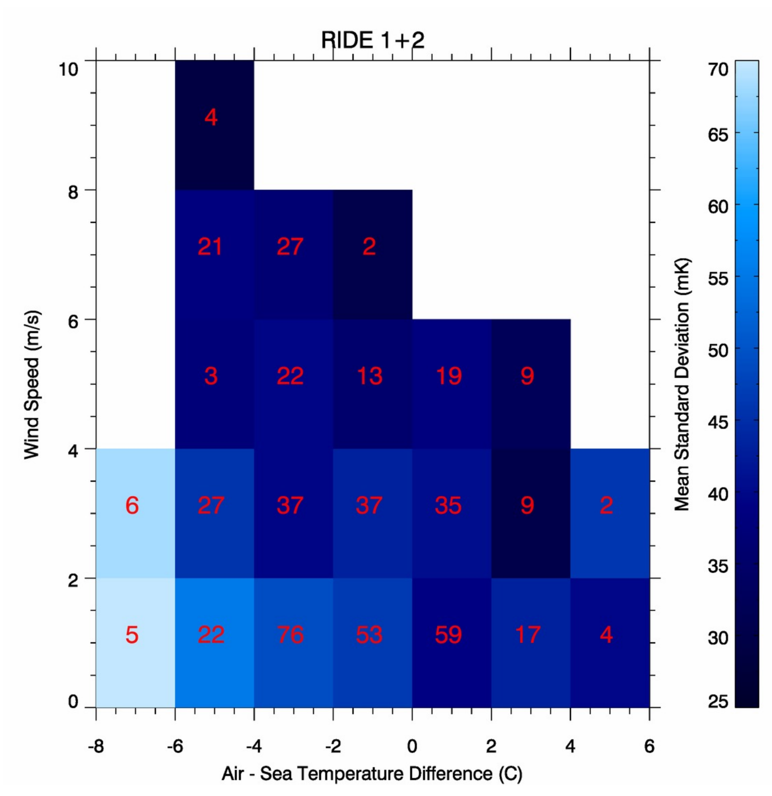

Figure 2: Temperature modulations from the emitted signal in the IR imagery as a function of air-sea temperature difference and wind speed binned into a 2°C by 2 m/s grid of air-sea temperature difference and wind speed. The color of the square indicates the average temperature standard deviation in mK for the data cases in that range. The red number indicates the number of data cases that went into that average.

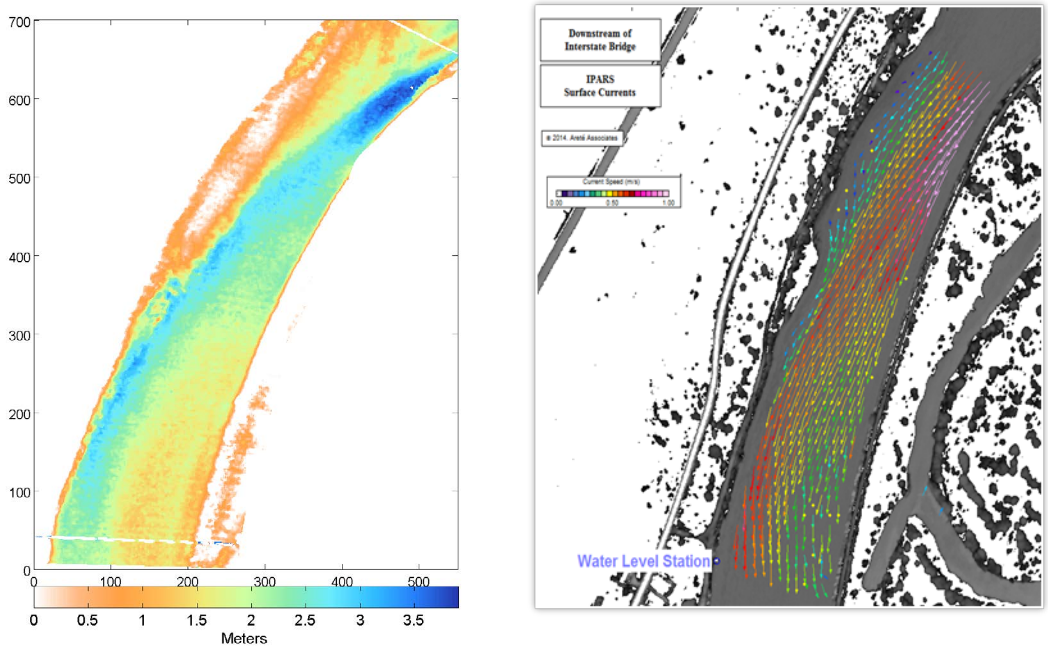

Figure 3. Example IRIS and PILLS data just upstream of the USBR station located below Interstate Bridge on the Lower Colorado River. The panel on the left shows the PILLS derived bottom topography. The panel on the right shows IRIS surface current retrieval. Note: The PILLS and IRIS data have not yet been precisely co-registered but clearly the strongest currents are collocated with the channel moving from the east to west bank traveling downstream.

it is possible to derive river discharge remotely. To derive discharge from the airborne data, we assume the depth averaged current is 86% of the observed surface current and integrate across the river. The U. S. Bureau of Reclamation maintains a real-time water level station at this site for direct comparison. The collocated discharge estimates were 7400 ft^3/s and 8200 ft^3/s for the airborne and USBR respectively.

IMPACT/APPLICATIONS

The U.S. Navy seeks to remotely sense the littoral, estuarine and riverine environments using unmanned systems. Knowledge of the environment will help assure mission success through better battlespace characterization and improved forecasting. The use of unmanned systems will eventually allow the Navy to characterize surface water dynamics and battlespace environments more efficiently and safely by using data only from remote sensors. In addition, the U.S. Geological Survey seeks to remotely sense river morphology and dynamics to improve its ability to monitor and predict surface water and sediment transport and validate their models.

RELATED PROJECTS

P.I. Christopher J. Zappa (LDEO Columbia University). *Remote Monitoring of Subsurface Flow Conditions in Rivers.* ONR Award Number : N00014-11-1-0922.

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