New compact wide-area, high-resolution, IR sensor for UAV platforms

Clayton R Chinn, Bill Morris, Brett Hooper
Areté Associates
Arlington, VA
cchinn@arete.com

Tom Reilly
Areté Associates
Tucson, AZ
treilly@arete.com

Abstract**—** The objective of the Defense Advanced Research Projects Agency (DARPA) RiverEye program is to retrieve accurate river surface current values over a wide area using passive optical remote sensors. An extension of this program included a requirement to develop, construct and demonstrate a small Mid-Wave Infrared sensor package to be the payload for a small unmanned aerial vehicle. To meet the restrictions imposed by the payload limitations an innovative fast scanning mirror technology developed by Areté was used. A description of the innovative sensor package that comprises this transition capability is given along with the results of the demonstration flights and processing.

Index Terms**—** *RiverEye, river currents, infrared, remote sensor, riverine, estuarine*

The views expressed are those of the authors and do not reflect the official policy or position of the Department of Defense or the U.S. Government. This is in accordance with DoDI 5230.29, January 8, 2009

I. Introduction

The Defense Advanced Research Projects Agency (DARPA) RiverEye program was designed to demonstrate a remote sensing capability for river surface current retrievals over a wide region using passive electro-optical sensors. The original visible program was extended in a second phase to demonstrate this capability using Mid-Wave InfraRed (MWIR) sensors. As part of this program there was a requirement to construct and demonstrate a transition capability with a small sensor package targeted for a small unmanned aerial system (UAS) platform. The RiverEye processing used to retrieve the river current values imposes certain demands on the MWIR sensor payload system including an ability to resolve the thermal and spatial features of river surface boundary layer's turbulent structure from an operational altitude while maintaining a field of regard sufficient to span across rivers of interest. System requirements also include sufficient temporal dwell to allow for a number of re-visits along with a navigation solution that produces stable mapped imagery for processing. In addition this sensor payload must meet the Size, Weight and Power (SWaP) restrictions to be able to be installed and operated on a small UAS or tactical unmanned aerial vehicle (TUAV) platform.

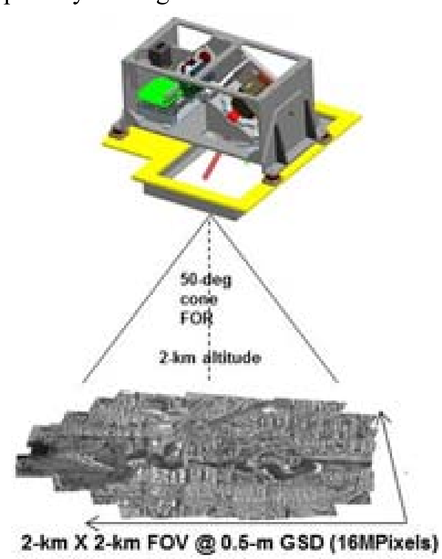


Figure 1: Schematic of sensor with field of regard over a collected mapped image is shown.

Existing IR sensor solutions, especially those which could meet the demanding RiverEye spatial and wide-area coverage requirements, are generally much too large, bulky and impractical for small UAS platforms. Areté Associates has developed a Fast Scanning Mirror (FSM) technology that is combined with a medium-size IR camera system (640x480 pixels) and optics to form a special, innovative sensor system that will meet the RiverEye requirements and fit within the limited SWaP of a typical small tactical UAS such as the Integrator made by Insitu, Inc. We are able to collect high-spatial resolution imagery of about 0.5 m ground spatial resolution at an altitude of about 2000 m with a commercial infrared camera and direct the imagery over a wide area recording at about 15 images per second. A readily available DRS MWIR 640-480 camera is used that allows for the collection of a continuously updated 60-96 image mosaic of the scanned ground scene during flight allowing the system to perform as an equivalent 9-15 Megapixel MWIR stabilized imaging system in a small, light-weight package.

Instead of using a sensor system with an exceptionally large focal plane array operating at a high frame rate that may lead to superfluous data, and exceed the SWaP and cost requirements, Areté has designed a sensor to optimize the space-time coverage in an efficient, small, light-weight package to meet the mission requirements. By integrating an available, affordable MWIR camera with the Areté-developed FSM, we are able to meet the high-spatial resolution demands, but also collect imagery over a wide area, and meet the temporal frequency and dwell requirements.

II. Sensor System Description

A mosaic approach is used to meet the collection requirements for this sensor system. The FSM steers the imaging system to collect a sequence of image tiles over the ground or water surface at a fast rate. An example is shown

978-0-933957-40-4 ©2013 MTS

below, where the image tiles are collected in a raster pattern to minimize the time between each tile and maximize the collection rate. The current system is able to collect at 12-13 image tiles per second, so a full frame or mosaic takes about 5 seconds. Future enhancements with improved scanning technology should permit scanning rates greater than 20 image tiles per second and by utilizing a HD format MWIR camera reducing the required number of overall tiles needed to form a frame.

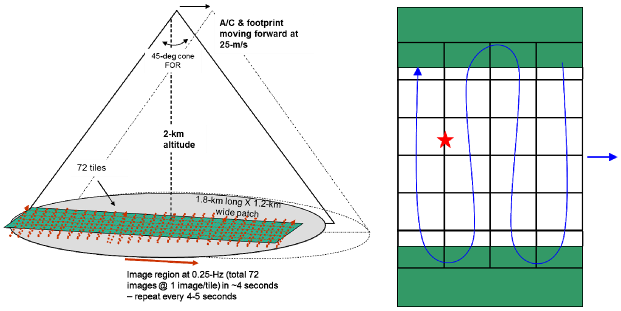


Figure 2: A schematic of the tile mosaic pattern is shown, where the left panel is the airborne scene, while the right panel displays the explicit raster pattern.

A number of engineering challenges were addressed to meet the requirements of the sensor system. It was critical to meet the sensor sensitivity requirements and maintain the thermal and radiance sensitivity needed to reveal the river water surface features necessary to retrieve the surface currents. An athermal optical design was adopted that proved to provide temperature tolerance from -20 to 60 °C and that maintained the Noise Equivalent Delta Temperature (NEΔT) of 20°-22° milliKelvin, which is very close to the sensitivity of the camera alone. A fold mirror design was used to meet the space restrictions of the transition platform and enable the steering mirror to image downward from the. A diagram of the design is shown below in Figure 3.

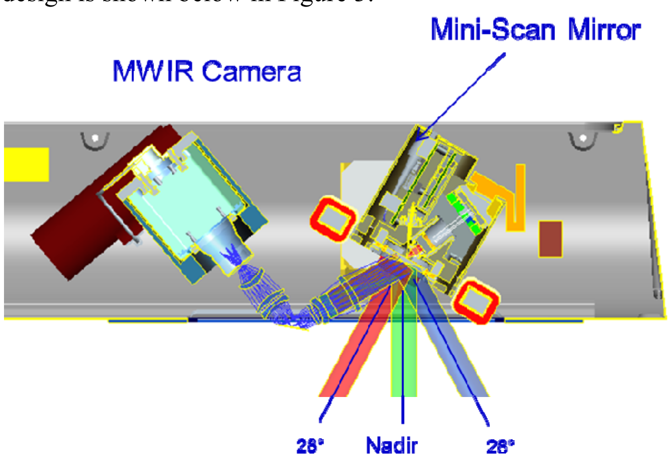
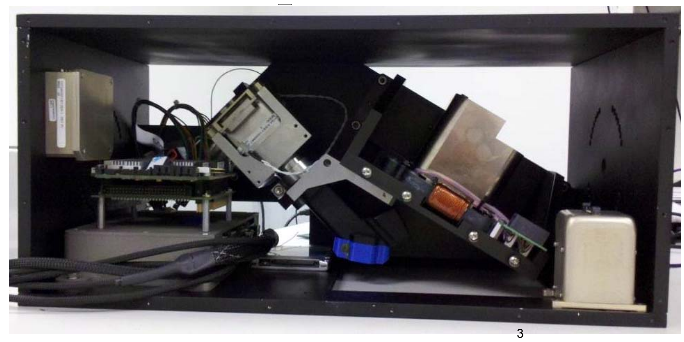


Figure 3: Shown is a rough design of the sensor system showing the camera, the mini-scan steering mirror or FSM, the fold mirror and the optics.

The prototype sensor system as shown in Figure 4 was packaged into a housing that was flown in a manned aircraft for flight demonstration. For eventual installation onto a small tactical UAS, the composite UAS structure would be



18” x 10.5” x 8” = 1,512 inches^3
Weight = ~45lb, ~20lbs housing & isolation

Figure 4: A picture of the sensor system in its demonstration installation within a simple housing. This configuration was used for the initial ECO and for the RIDE4 data collections. For installation into the final TUAV configuration it will be necessary to reconfigure the componets slightly and leverage the existing composite UAS structure to support the system housing. Such a configuration should easily meet the SWaP restrictions for the Insitu Integrator platform.

leveraged to support the system housing during design and construction.

The sensor system operation consists of 3 different collection modes. Mode 1 – was designed for system testing and uses of a set of fixed angles for each tile location in the mosaic, where the angles are relative to the aircraft or sensor base. Mode 2 – is also a set of fixed angles, but in this case the angles are relative to the inertial frame, where aircraft motion is removed using the attitude information provided by the Inertial Navigation System (INS) in real-time. In addition Mode 2 incorporates forward motion compensation (FMC) where motion blur due to aircraft motion is minimized by compensating for the motion of the sensor platform via an imposed steering mirror angle rate that opposes the aircraft motion effect. Mode 3 – was designed to meet the collection requirements for current retrieval processing and is the most advanced collection mode used. In this case a set of aimpoints is uploaded into the control software using Latitude/Longitude/Altitude in GPS coordinates for ground control points. The sensor system then points to the aimpoints on the ground provided they fall within the field of regard of the system. This approach results in image tiles collected about each aimpoint for those sweeps or frames where the aimpoint falls within the field of regard. Mode 3 also incorporates FMC. The modes are summarized in Table 1.

Table 1: A list of the collection modes that are currently configured into the system control software is given.

Mode	Description
1	Fixed relative angles with respect to the aircraft platform
2	Fixed relative angles with respect to the inertial frame and includes FMC
3	Sensor points to explicit set of ground aimpoints and includes FMC

III. Processing Challenges

There were a number of processing challenges to be overcome to enable the RiverEye current retrieval algorithms to operate on the image data recorded by this sensor system. The current retrieval requires registered and stabilized mapped imagery, since any errors or inaccuracies in the registration and mapping would translate into errors in the retrieved current values. The accuracy provided by the INS and the steering mirror is more than adequate for controlling where to point the mirror and for collecting the image tile mosaics, but leaves multiple-pixel errors in geo-registration and subsequent mapping. The current retrieval processing required much better accuracy than provided by the hardware therefore post-processing image registration is needed. Specific challenges noteworthy for this application are listed and described briefly below:

1. FSM Settling Time - In addition to the difficult challenges of configuring the control software for the FSM there was an additional challenge to minimize the impact of motion blur in the imagery. When the mirror is commanded to slew to a new orientation, there is residual motion needs to settle down to a degree such that the image focus is not impacted. In this case the RMS jitter, which is related to the encircled energy or fraction of the radiance that falls within each pixel, is calculated to provide feedback in the control loop. The control software, operating at 10 kHz, uses this information to determine when the camera is to be triggered to expose an image. During the development and testing of the system certain parameters associated with the feedback information were tuned to minimize any motion blur due to the residual mirror slewing motion.
2. Over-water registration – this part is especially challenging. Test MWIR imagery had been collected using prior systems where it was found that there is a great deal of fine-scale structure available for registration. Using this prior MWIR water imagery, it was demonstrated that over-water registration was doable and could be robust. In this case the registration was performed using both Mutual Information and cross-correlation techniques. Note that the mosaic raster pattern is designed to minimize the time between adjacent tiles thus maximizing the coherence between the subsequent, neighboring images.
3. Mapping of the imagery – The collected tile imagery must be mapped prior to registration and ground-stabilization. Using the camera optics distortion calibration results and the sensor pointing information, the imagery is mapped to the ground plane using methods and software derived from experience. Samples of mapped imagery are shown below.

IV. Results

The sensor system as configured has flown and collected imagery using a number of different platforms beginning in August, 2011 and extending through November, 2011. These collections included a number of test flights over land in Arizona on two different Cessna planes in August-September, 2011, a long RiverEye deployment over a number of rivers in September-October, 2011 on a Twin Otter aircraft, and some additional land collections in October-November, 2011 in Arizona again on a Cessna airplane.

For the RiverEye RIDE4 deployment, the base of operations was initially in Grand Junction, Colorado at the Twin Otter International facility. The rivers that were imaged were the Colorado, Green and Yampa Rivers. Base of operations changed to Pocatello, Idaho to cover different sections of the Snake River and then to Pasco, Washington where collections took place on the much larger Columbia River with one collection over the ocean near Yakima, Oregon. Sample overviews are shown below of the river collection areas showing the various cases.

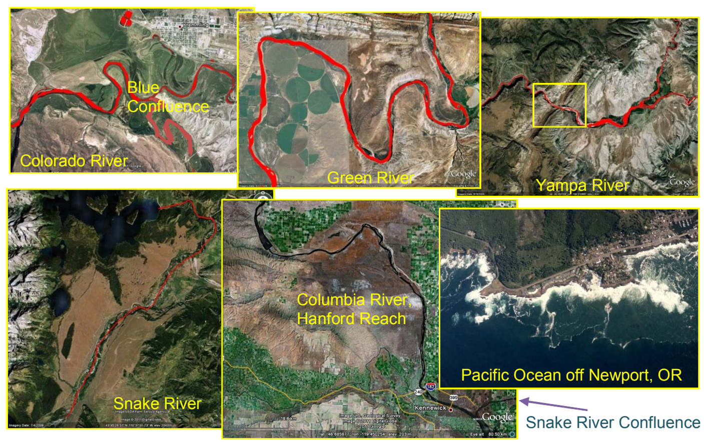


Figure 5: A montage of images of the rivers from which image data was collected during the RIDE4 deployment. These include portions of the Colorado, Green and the Yampa Rivers near Grand Junction Colorado; the Snake River near Pocatello, Idaho and the Columbia River North of Pasco, Washington. In addition an open ocean collection off the Oregon coast was made.

For the RIDE4 deployment, three different sensor systems were employed to collect image data. A set of two MWIR fixed FLIR one megapixel cameras were used as well as a set of two visible pan-chromatic eleven megapixel cameras for comparisons.

For the standard Mode 3 collection, the geographic aimpoints for the collection are set up to make out a rectangular mosaic over the region of interest, which for RIDE4 was over a river. The aimpoints could be configured to be an arbitrary number of tiles wide to make up the mosaic. For the RIDE4 deployment the mosaic was set to 6 or 8 tiles wide. Shown below in Figure 6, is a sample of an 8 tile wide collection. The flight path is moving in the upwards direction in the figure, with the aircraft flying at about an altitude of 8000 ft. The corresponding ground spatial resolution was about 0.6 m with the full mosaic about 2 km wide.

Figure 6 Shown is a large 8 tile wide mosaic where the flight path is upward in the figure. This mosaic of images was collected over a freeway intersection near Pasco, WA.

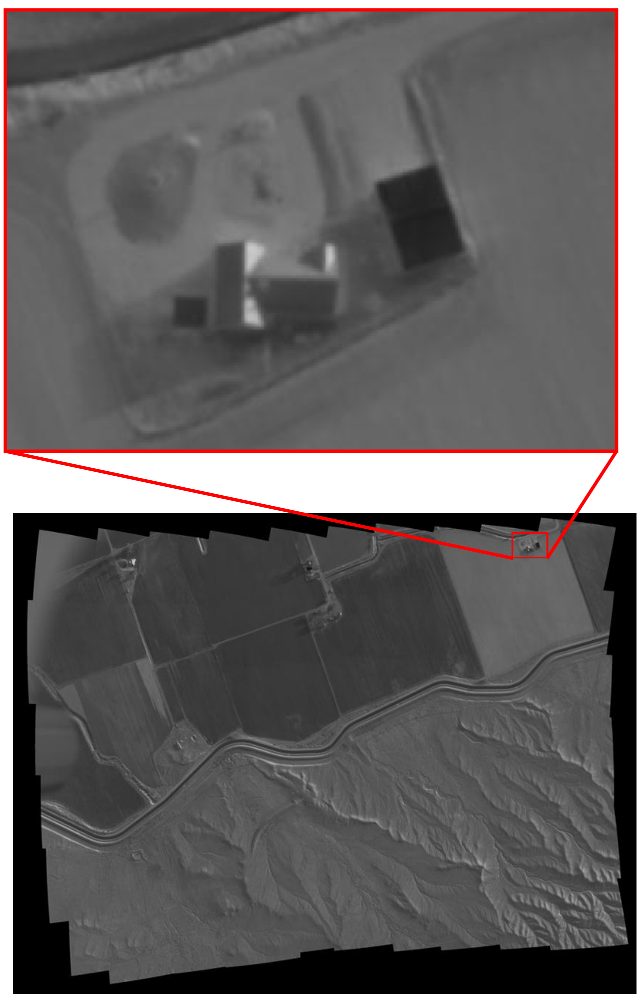


Figure 7: 60 image tiles are registered, mapped and stitched together to produce a single large image. A zoomed section of the image is expanded to reveal the details in the high-resolution imagery.

Using registration techniques the mosaic of tiles can be aligned and stitched together to produce a single large image. An example of this process over a land scene is shown in Figure 7. An expanded view is shown in an insert to reveal the fine, high-spatial resolution details.

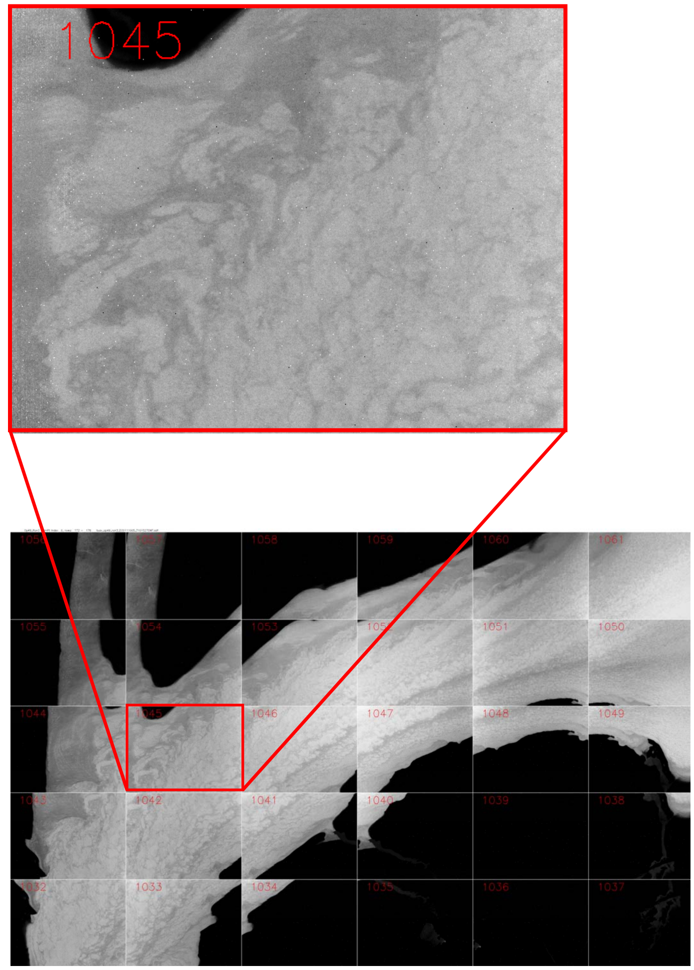


Figure 8: A mosaic of tile images is shown for a nighttime collection over the Columbia River North of Pasco, WA. A zoomed view at half the true image size of one of the tiles reveals the MWIR river surface features.

For the RiverEye current retrieval processing the sensor imagery must be able to reveal the high-spatial resolution river surface features. A sample set of tile images in Figure 8 reveals these necessary surface details, both in the large image and in the expanded insert. The radiance sensitivity for the sensor system was found to easily meet the requirements for successful current retrieval processing.

The original Mode 3 collection mode was designed to handle straight sections of rivers. As is clear from Figure 5, assuming straight sections poses a CONOPS challenge to collect useable image data over natural rivers. For Mode 3 it turns out that the control software is able to handle the meandering of the rivers in a straightforward manner. In this case an extra-wide mosaic of geographic aimpoints is set up on the ground about the river. As the plane flies over the river, the control software will only process and collect imagery over an aimpoint if it falls within the field of regard of the sensor system, *i.e.* the steering mirror is able to point in that direction. In other words as the control software proceeds through the list of aimpoints, if the next aimpoint in the list in the mosaic falls outside the field of regard, then that aimpoint is skipped and the control software proceeds to the next aimpoint in the list. This calculation is very fast and does not pose any delay in the collection. It is expected that a mosaic of aimpoints can be set up to fit within a rectangular grid and that the data collection can be designed to only include in the mosaic list those aimpoints that are of interest about a river. This would present a very efficient collection modality and should fall within the capabilities of the Mode 3 configuration and control software. Figure 10 is a sample of an 8-wide mosaic, where the pilot of the aircraft was instructed to follow the river and the control software was able to easily and successfully collect relevant imagery for those aimpoints that fall within the field of regard of the sensor system.

A demonstration of the RiverEye current retrieval as applied to image data collected using this sensor system is shown in Figure 9, where the current retrieval results shown in the right panel display match very well the results obtained using the other fixed sensors.

As part of the RIDE4 collection an open ocean collection was performed on one day off the Oregon coast. A mapped frame of a mosaic is shown in Figure 11 of a coastal ocean scene near Yaquina Head, Oregon.

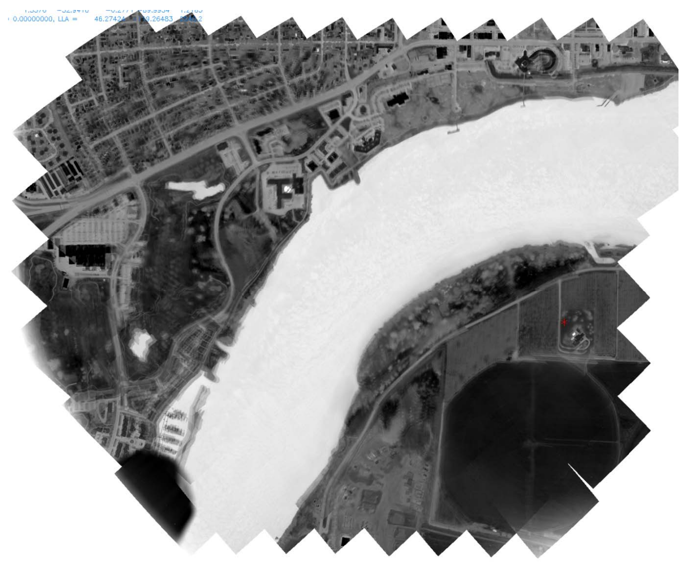
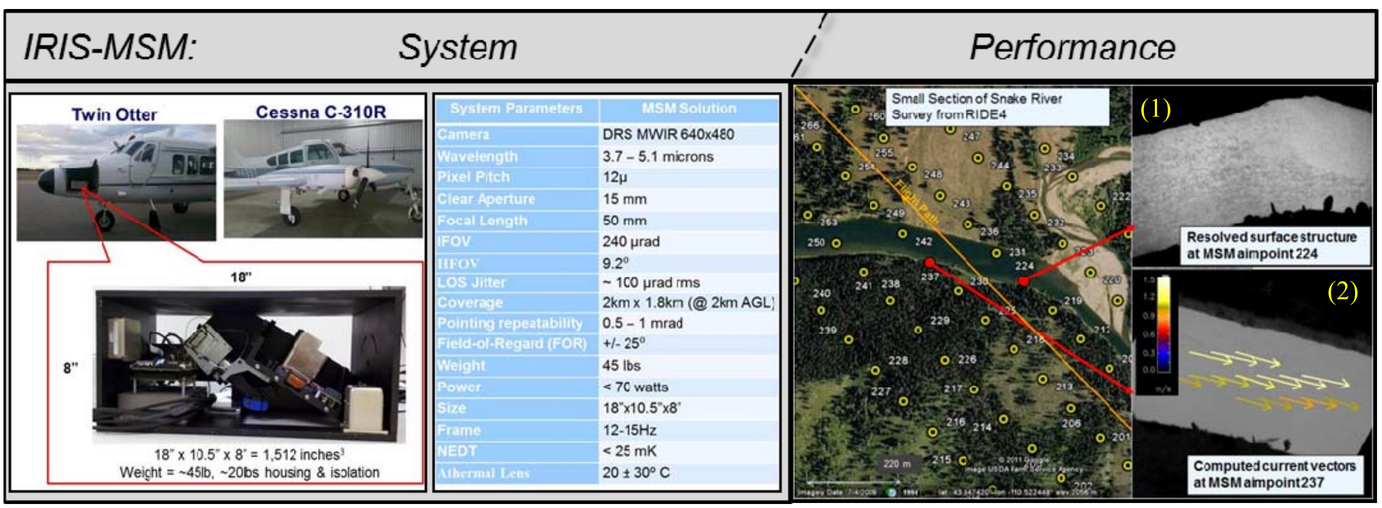


Figure 10: Mapped tiles are stitched together to form a mapped single image over the Columbia River. This nighttime image shows the Columbia River as it meanders, revealing the river surface structure. The pilot of the aircraft was instructed to follow the river. Here the control software was able to easily and successfully collect Mode 3 imagery over those aimpoints that fall within the sensor system field of regard.



System Parameters	MSM Solution
Camera	DRS MWIR 640x480
Wavelength	3.7 – 5.1 microns
Pixel Pitch	12µ
Clear Aperture	15 mm
Focal Length	50 mm
IFOV	240 µrad
HFOV	9.2°
LOS Jitter	~ 100 µrad rms
Coverage	2km x 1.8km (@ 2km AGL)
Pointing repeatability	0.5 – 1 mrad
Field-of-Regard (FOR)	+/- 25°
Weight	45 lbs
Power	< 70 watts
Size	18"x10.5"x8"
Frame	12-15Hz
NEDT	< 25 mK
Athermal Lens	20 ± 30° C

Figure 9: The summary chart depicting (left panel) the prototype system flown on Twin Otter and Cessna aircraft during a series of engineering check-out and demonstration flights, (center panel) the measured specifications of the IRIS-MSM imaging system, and (right panel) Google-Earth map of the RIDE4 demonstration showing flight path with MSM-aimpoints over Snake River, WY and arrows identifying the locations of: (1) an example IRIS-MSM image showing the resolved river surface structure and (2) processed current estimates on ~70-m wide section of Snake River. The processing uses a Fourier-based technique performed on 32 m boxes for each current retrieval calculation.

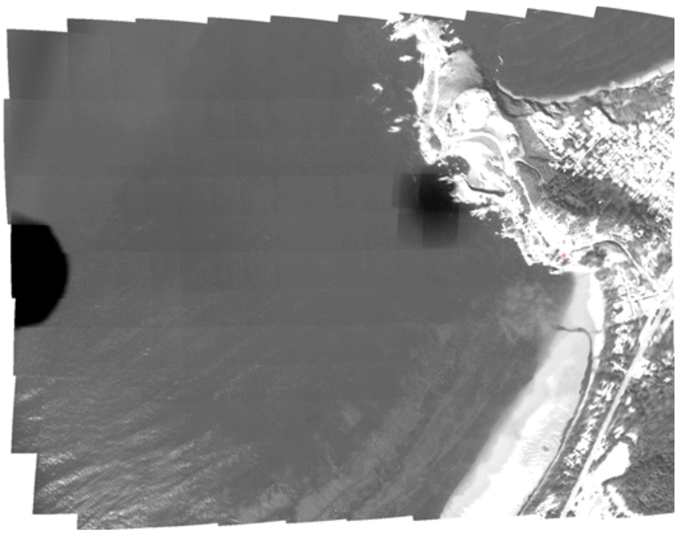


Figure 11: Shown is a mapped frame of tile image tiles covering about a 2 by 2½ km area from the sensor system taken over the ocean near Yaquina Head, OR. The dark circle to the left is due to the wheel of the Twin Otter aircraft. The dark smudge near the center is from some temporary damage to the special coating of the IR-transparent window of the sensor system.

V. Conclusion

For the DARPA RiverEye program a small specialized sensor system was developed, constructed and demonstrated using a COTS MWIR camera coupled to a fast steering or scanning mirror with athermal optics. The sensor system was designed to meet the SWaP restrictions for a small TUAV such as the InSitu Integrator (RQ-21A). The system was successfully flown and demonstrated for both over-river collections for the RiverEye program and over-land scenes. Software developed at Areté Associates enables mapping, registering and stitching the image data to produce mapped imagery equivalent to a much larger 9-15 megapixel sensor system.

This unique and innovative sensor package could also be used for Intelligence, Surveillance and Recognizance (ISR) operations over the open ocean, littoral regions or land. The sensor provides a wide-area view of a scene with a relatively high spatial resolution at a moderate frame rate in a small, light, low-power package. Such a system could be used to provide wide-area coverage to cue a complex sensor that may have a very limited field of view.