United States Department of Agriculture
Forest Service

Wide Area Imager Fire Mapping Evaluation Mission

November 2014

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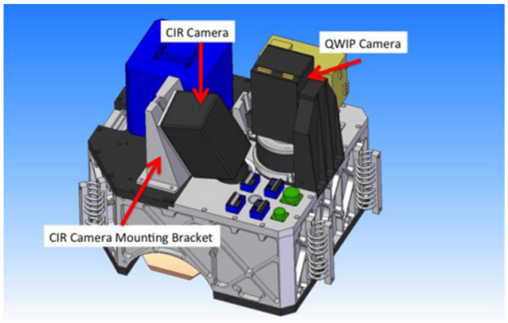

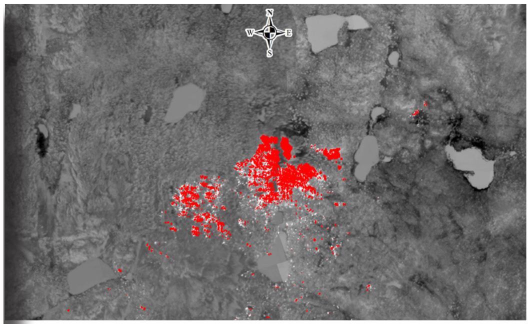

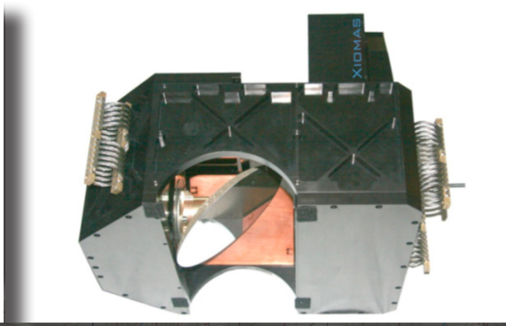

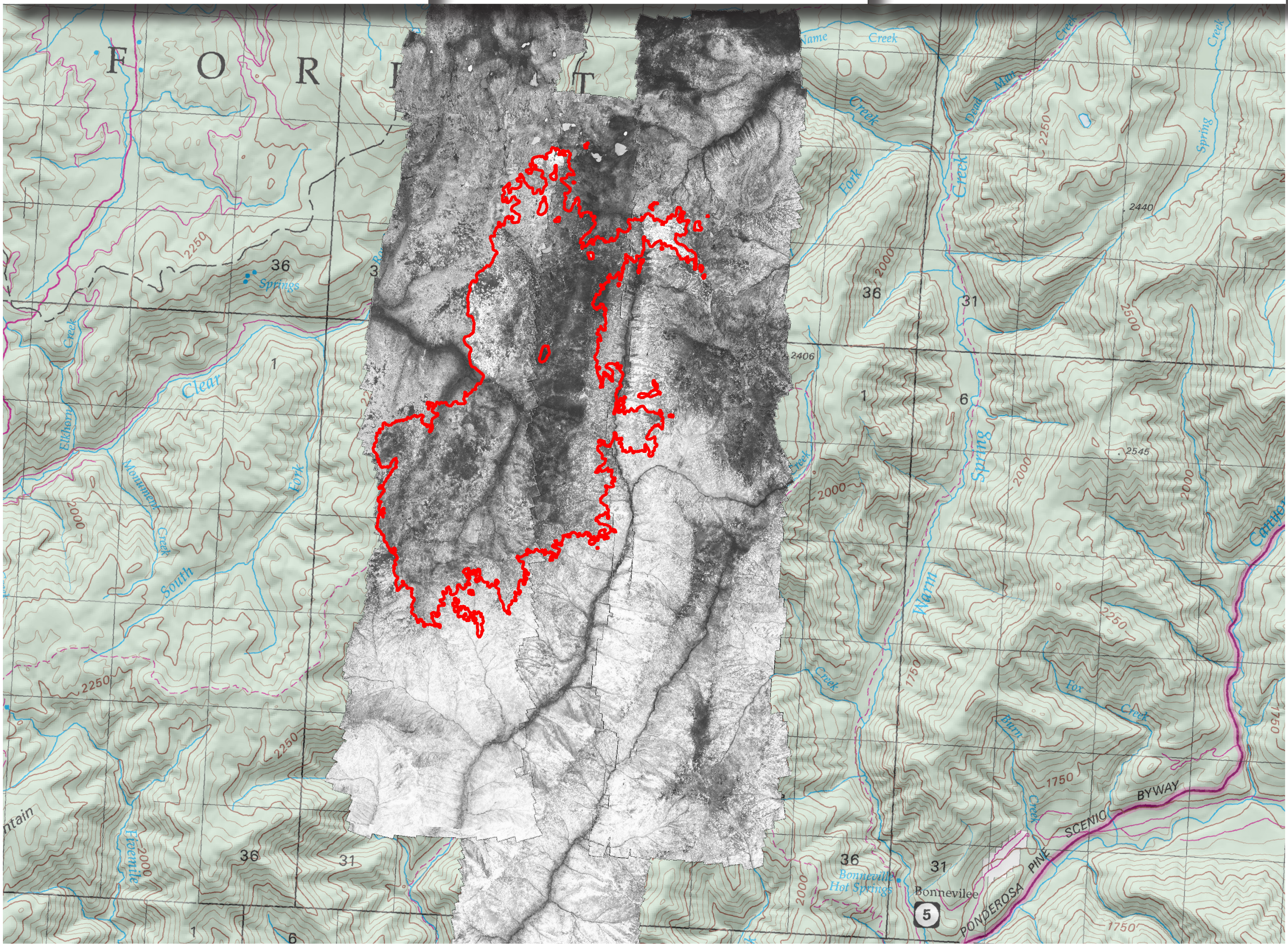

Abstract

The Wide Area Imager (WAI) Fire Mapping Evaluation Mission was a multi-day mission conducted July 23-26, 2013 to operate the WAI sensor over active fires and measure operational fire parameters. The WAI sensor was evaluated in an operational environment to assess its capabilities for tactical scale active fire detection and mapping support. High-resolution thermal infrared imagery of active wildfires was provided to staff from the Forest Service, U.S. Department of Agriculture, Remote Sensing Applications Center staff for evaluation. A review of the WAI thermal infrared imagery and fire detection products was conducted to determine their utility in deriving standard tactical fire mapping/geospatial products. This evaluation mission was the first test of the WAI in an operational fire mapping situation. There were no significant operational issues with the airborne thermal imaging system, or the output imagery. With some sensor system refinements, the WAI could be integrated into the Forest Service operational fire support environment.

Keywords

NIROPS, National Infrared Operations, WAI, Wide Area Imager, RSAC, Remote Sensing Applications Center, Xiomas, Phoenix, infrared, thermal, MWIR, mid-wave infrared, LWIR, long-wave infrared, MWIR/LWIR ratio, interpretation, fire, wildfire, mapping, CIR, color infrared, sensor

Authors

Jan Johnson is a remote sensing specialist employed by RedCastle Resources, at the Remote Sensing Applications Center (RSAC) in Salt Lake City, Utah.

Mark Finco is a contract leader for RedCastle Resources at RSAC.

Brad Quayle is the program leader for the Rapid Disturbance Assessment and Services group at RSAC.

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Introduction

The Wide Area Imager (WAI) airborne sensor was developed by Xiomas Technologies LLC under the NASA Small Business Innovation Research (SBIR) program. Xiomas worked with NASA and Forest Service personnel during the development process to incorporate operational requirements and the latest technologies in the design of the WAI. The overall goal of the WAI SBIR project was the development of an airborne sensor that will increase the efficiency of the Forest Service National Infrared Operations (NIROPS) program by covering more ground in less time and with a similar or higher spatial resolution than the currently-fielded sensor. If successful, this technology has the potential to reduce aircraft and crew operating costs of the NIROPS program and to increase crew safety.

The WAI sensor was at Technology Readiness Level 7 (TRL 7) at the time of the fire mapping evaluation mission. TRLs are a type of measurement system used to assess the maturity level of a particular technology. There are nine technology readiness levels, with TRL 1 the lowest (scientific study) and TRL 9 the highest (mission proven). TRL 7 means the sensor prototype is ready for demonstration in an operational environment; it is at or near the specifications of the operational system; it has been integrated with ancillary systems; and the majority of its functions can be demonstrated and evaluated.

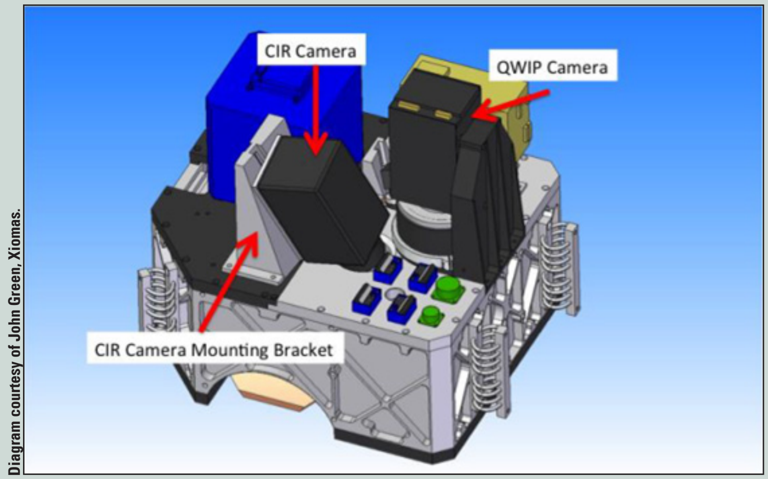

Figure 1—A CAD model of the Wide Area Imager (WAI) showing the configuration of the QWIP camera and the CIR camera. The CIR camera is offset from a nadir view, pointing to the right and aft, in order to fit it into the sensor system.

Objectives of the Fire Mapping Evaluation Mission

This evaluation mission was conducted with two desired objectives. The first was to deploy the WAI sensor over active fires and measure operational fire parameters. The WAI sensor was evaluated in an operational environment to assess its capabilities for active fire mapping support. High-resolution thermal infrared imagery of active wildfires would be collected and provided to staff from the Forest Service Remote Sensing Applications Center (RSAC) for evaluation of its utility in deriving standard tactical fire mapping/geospatial products. The WAI imagery would be reviewed and qualitatively assessed in the context of NIROPS thermal imagery, collected with the Phoenix sensor and acquired near contemporaneously for the same wildfires, and the systematically derived fire detection products.

A second objective of the evaluation mission was to collect daytime high resolution visible/near infrared (VNIR) imagery using the WAI color infrared (CIR) camera in order to evaluate the sensor's ability to provide daytime imagery of wildfire incidents and to corroborate/validate satellite-based assessments of burn severity.

Overview of the Wide Area Imager System

The WAI is a multi-band sensor system that utilizes "step-stare" image acquisition and a Quantum Well Infrared Photo detector (QWIP) focal plane array (FPA) to collect co-registered mid-wave and long wave infrared imagery. The step-stare system is similar to a line scanner system, but instead of a continuously spinning mirror, the mirror rapidly steps in small increments across the field of view, acquiring a series of images. This allows for high spatial resolution across a wide field of view. QWIP are a class of photo detectors that utilize photosensitive materials with holes, or "wells" etched into the material to control the wavelength(s) being collected. As QWIP are narrow band detectors, multiple QWIP must be layered, or stacked, in order to acquire imagery across multiple wavelengths. The QWIP FPA in the WAI consisted of a two-layer stack, one layer sensitive to a portion of the mid-wave infrared wavelengths (4.4–5.4 µm) and the other sensitive to a portion of the long wave infrared wavelengths (8–9 µm). The system also has a co-located CIR camera for daytime imagery acquisitions (figure 1). The CIR camera does not collect nadir viewing imagery coincident with the QWIP camera as it is pointed to the right and aft of the QWIP camera.

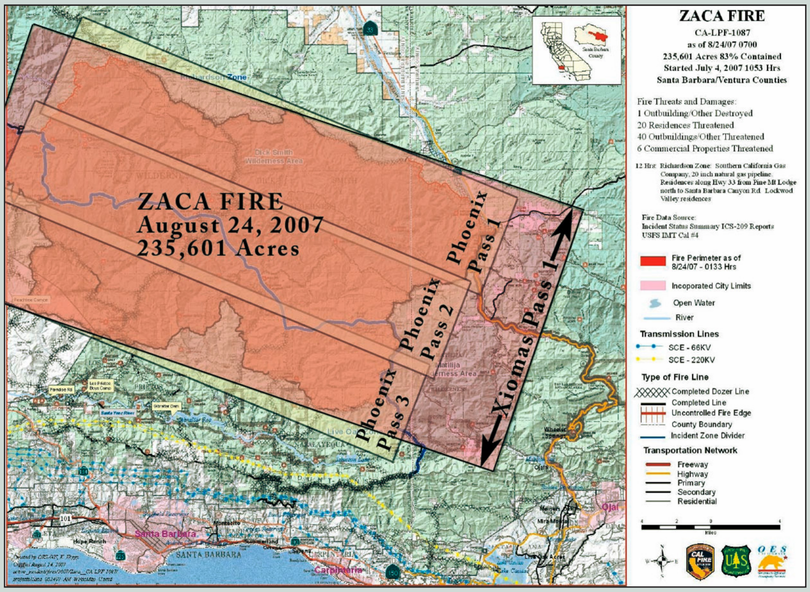

Figure 2—The WAI has an estimated swath width of approximately 15 miles when flown at its design altitude of 40,000 feet ASL. The figure shows the WAI coverage of the 2007 Zaca Fire from 40,000 feet ASL compared to the Phoenix coverage of the same fire from 14,000 feet ASL.

The WAI prototype used in the mission has an instantaneous field of view (IFOV) of 100 to 300 µrad and a field of view (FOV) of 90⁰. This yields an ortho-rectified pixel size of 3.5 meters and a swath width of 15 miles when it is flown at its design altitude of 40,000 feet above sea level (ASL). At that altitude the sensor has an estimated capability to detect an 8 square inch 600° C heat source. Figure 2 shows the estimated areal coverage of the WAI when flown at its design altitude. The WAI utilizes aircraft attitude and location data from an Applanix POS AV Inertial Measurement Unit (IMU) combined with 10-meter National Elevation Data (NED) to ortho-rectify and mosaic the collected thermal imagery in real time. The thermal imagery is output as two single-band 16-bit (0-65,535 grey levels) images in JPEG2000 format. A derived fire detection layer, created using a ratio of the measured mid-wave infrared (MWIR) and long-wave infrared (LWIR) values, is also produced, and output as a raster file.

For comparison, the NIROPS Phoenix thermal line scanner system has an IFOV of 1.25 milliradians and an FOV of 120⁰. This yields an ortho-rectified pixel size of 3.5 meters at nadir and a nominal swath width of 6 miles when flown at an altitude of 10,000 feet above ground level (AGL). The heat source detection threshold at 10,000 feet AGL is an 8 square inch object at a temperature of 600° C. The Phoenix system also utilizes aircraft attitude and location data from an Applanix POS AV IMU combined with 30-meter NED to ortho-rectify the collected thermal imagery in real time. The thermal imagery is output as 2-band 8-bit (0-255 grey levels) imagery in GeoTiff format. A derived fire detection layer, created using a ratio of the measured MWIR and LWIR values, is also produced, and output as a vector file. Table 1 shows the system specifications for the WAI and Phoenix.

Table 1—Phoenix and WAI system specifications

System	Number of Bands	Wavelength	Spatial Resolution	Quantization	IFOV[1]	FOV (degrees)[2]	Production Rate (acres/hour)
Phoenix	2 (Thermal)	3-5 µm, 8-12 µm	3.5 m @ 10,000 AGL	8-bit (0-255)	1.25 mrad	120	300,000
WAI	2 (Thermal)	4.4-5.4 µm, 8-9 µm	3.5 m @ 40,000 ASL	16-bit (0-65,536)	100-300 µrad	90	2,900,000
	3 (VNIR)	0.5-0.6 µm, 0.63-0.69 µm, 0.76-0.90 µm	0.46 m @ 10,000 AGL	8-bit (0-255)	150 µrad	16 x 9	

[1] Instantaneous Field of View in milliradians (mrad) or microradians (µrad).
[2] Field of View.

The Wide Area Imager Evaluation Mission

The WAI prototype was installed in a Photo Science Inc. (now Quantum Spatial Inc.) Piper Navajo that was ferried from Lexington, Kentucky to Boise, Idaho on July 23, 2013 (figure 3). All of the necessary system integration and sensor calibration work, including a sensor bore sight calibration, was completed prior to the evaluation mission. Due to adverse weather conditions in the Lexington area, the calibration mission was not completed until July 12, 2013. The imagery from the July 12 mission was geo-coded and ortho-rectified during the mission using bore sight calibration parameters from a previous mission, as there was not enough time to send the imagery, position and orientation data to a vendor to derive a new set of calibration parameters. This solution produced an adequately registered output product, but added a degree of uncertainty regarding the potential positional accuracy of the imagery for the evaluation mission.

The evaluation mission was conducted over three nights, starting on the night of July 23/24 and concluding on the night of July 25/26. The aircraft departed Boise around 2200 Mountain Daylight Time (MDT) each night and traveled to the area of operation, with imagery acquisition occurring between 2230 and 0200 MDT. Four active wildfire incidents, located northeast of Boise, were targeted for the WAI evaluation mission (figure 4). The number of fires imaged each night varied. The thermal imagery was acquired at an altitude of 17,000 feet ASL (8,000–9,000 feet AGL). As the WAI was being operated at a low altitude, the FOV was reduced from 90⁰ to 45⁰ degrees to avoid excessive imagery overlap between the flight lines.

Photo courtesy of John Green, Xiomas.

Figure 3—The WAI sensor prototype as installed in the Photo Science Piper Navajo.

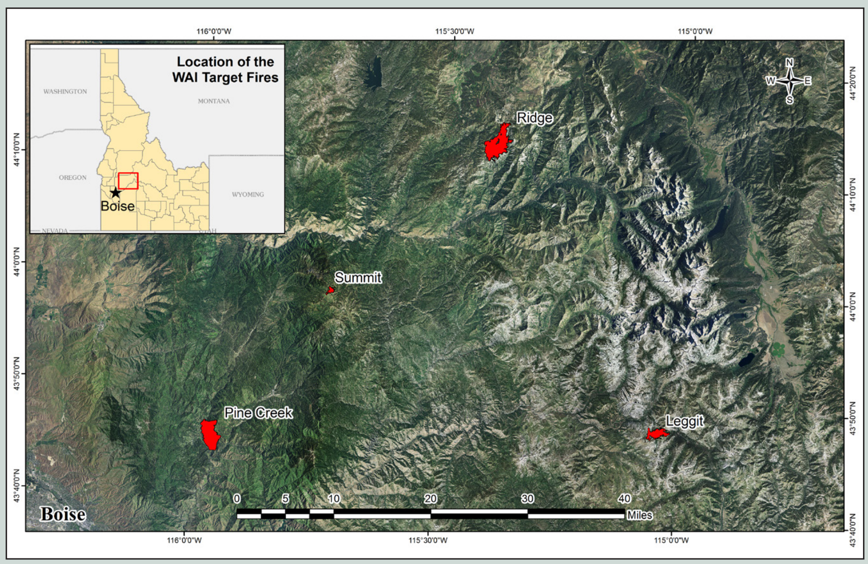

Figure 4—Shown here are the fires that were imaged with the WAI during the evaluation mission. Phoenix and WAI thermal imagery was acquired for the Ridge and Leggit fires on two nights of the evaluation. Only WAI thermal imagery was acquired for the Pine Creek and Summit fires.

During the WAI evaluation mission period, operational infrared imagery collection was conducted by NIROPS at the request of the incident management teams for two of the incidents. Table 2 shows the dates and times that WAI and Phoenix imagery was acquired for the target fires.

Table 2—Fires overflown during the WAI evaluation mission

Mission	Date	Fire Name	WAI Start Time (MDT)	Phoenix Start Time (MDT)
1	7/24	Ridge	0030	0202
2	7/24	Ridge	2259	2227
	7/25	Pine Creek	0022	
	7/25	Summit	0040	
3	7/25	Ridge	2246	0326
	7/25	Leggit	2336	0342
	7/25	Summit	2359	
	7/26	Pine Creek	0032	

Mission Deliverables

Daily mission briefings/reports were submitted to the RSAC staff in Boise. Pre-mission briefings outlined the mission plan prepared by Xiomas and Photo Science, while post-mission reports included delivery of the imagery mosaics and derived fire layers, applied sensor settings/thresholds, notes of in-flight observations by the operator, and a verbal mission briefing. The Xiomas scientist also met with the RSAC staff prior to each flight to review the previously acquired imagery and discuss any anomalies found during the imagery evaluation.

Imagery Evaluation

RSAC staff evaluated the daily WAI imagery mosaics using several criteria, including:

- Imagery/Product Latency: Timeliness in the availability of processed WAI imagery and derived products. All WAI image processing was conducted onboard the aircraft in near real-time and delivered for review at the completion of each day's mission.
- Completeness of Coverage: Inspection of the WAI imagery for comprehensive coverage of each targeted fire area and any coverage gaps between or within the flight lines. The spatial extent of imagery mosaics was compared to the location and extent of current fire perimeter data to verify complete imagery coverage for each fire. Imagery was visually inspected to identify and document the presence of intra- and inter-flight line image gaps. Further analysis and discussion were conducted with the Xiomas scientist as needed to determine sources of any image gap issues.
- Imagery Quality and Interpretability: Assessment of the general quality of the WAI imagery and its interpretability for identifying and characterizing fire activity. Imagery was reviewed in the context of 1) temporally coincident Phoenix thermal imagery to assess its use for identifying intense, scattered and isolated fire activity, and 2) Idaho 1 meter resolution National Agriculture Imagery Program (NAIP) imagery acquired in 2011 to evaluate its utility for identifying physical features.
- Imagery Ortho-rectification: Inspection of the imagery ortho-rectification results by visual inspection of an overlay of the WAI imagery mosaics with corresponding 2011 Idaho NAIP imagery. Visually detectable position shifts in prominent features such as roads were identified and measured. Further analysis and discussions were conducted with the Xiomas scientist as needed to identify potential sources of error.
- Utility for Fire Mapping: Evaluation of the utility of the WAI imagery as source imagery for producing tactical scale fire mapping products. Vector products compiled from Phoenix imagery by Forest Service infrared interpreters were overlaid on the WAI imagery mosaic. A visual assessment was conducted to determine if the interpretation of the WAI imagery would yield similar fire mapping products. An additional assessment was conducted to compare the derived fire detection layer from the WAI and Phoenix systems.
- Visible/Color Infrared: Not evaluated. Daytime WAI visible/color infrared (CIR) imagery was not acquired during the evaluation mission. Ground tests of the CIR camera conducted by Xiomas in June 2013 prior to and after installation in the Photo Science aircraft showed no problems. Ground tests conducted in July prior to ferrying the aircraft to Boise for the evaluation mission showed a malfunction in the CIR camera that could not be diagnosed or corrected prior to the evaluation mission.

Results

Imagery/Product Latency

All WAI image processing was conducted onboard the aircraft in near real-time and delivered for review at the completion of each day's mission. Eight sets of WAI LWIR imagery and LWIR/MWIR fire layers, in JPEG2000 format, were delivered to the RSAC staff in Boise over the 3 days of the evaluation. The imagery and products were delivered on a USB-enabled hard drive within 1 hour of the completion of the mission. This was well within the 6 hour delivery window specified in the evaluation mission statement of work (SOW). The MWIR imagery was collected during the missions, but was delivered to the RSAC staff after the evaluation mission was completed. The later delivery of the MWIR imagery was requested by Xiomas to allow them to refine their imagery post-processing routine.

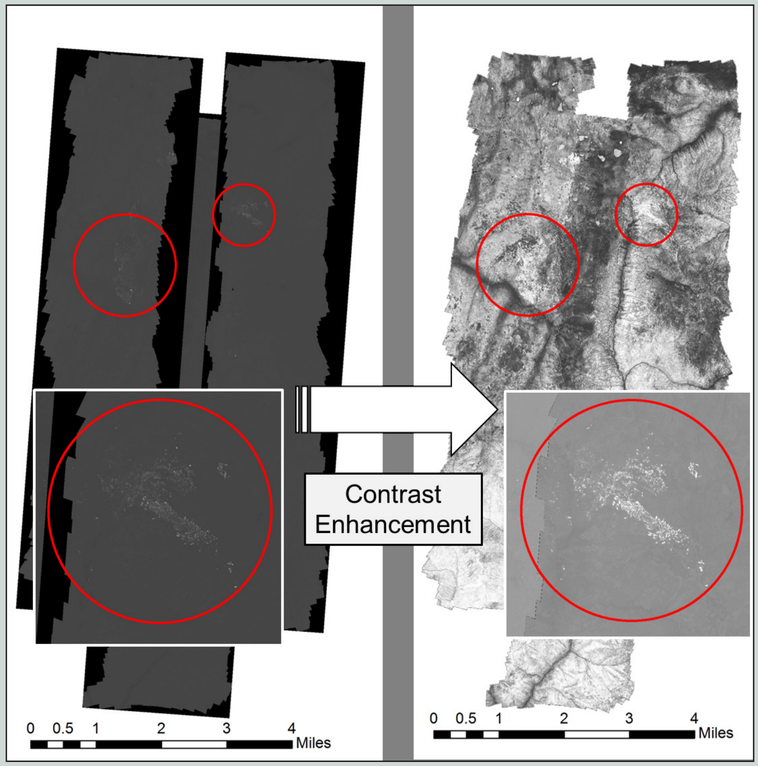

Figure 5—The WAI LWIR imagery mosaics before *(left)* and after *(right)* contrast enhancement. WAI thermal imagery is acquired as "white is hot". The red circles indicate areas of intense fire activity that were visible on single image strips before *(and after)* contrast enhancement. The inset images provide a closer view of the smaller *(right most)* circles.

Completeness of Coverage

The geographic extents of the individual fires were covered, and visual inspection of the imagery by the RSAC staff determined that there were no imagery gaps between the flight lines on any of the fires or within the imagery mosaics that comprised the individual flight strips. From an evaluation viewpoint, having complete geographic coverage of the fire allowed the RSAC staff to compare the WAI imagery to the corresponding Phoenix imagery across the entire fire and a range of fire activity levels.

Image Quality and Interpretability

The WAI LWIR mosaics of the fires had a spatial resolution of 0.66 meters, which provided a level of detail that was more than adequate for visual interpretation and delineation of fire activity. Topographic and cultural features present in the 2011 Idaho NAIP imagery were readily identifiable in the thermal mosaics. The imagery mosaics were contrast enhanced to enable the user to discern and interpret background detail plus scattered and isolated heat sources. It should be noted that areas of intense fire activity were visible before any contrast enhancement was applied to the imagery (figure 5). Sample LWIR imagery sent to the RSAC staff by Xiomas from a thermal discharge mission in January 2013 also had very good spatial resolution, though it too had to be contrast enhanced before the imagery detail became visible.

Basic image enhancement techniques applied to the LWIR imagery allow the interpreter to put the fire activity into the context of the landscape (figure 6 and 7). This is important from an operational viewpoint as discernible features such as roads, streams, and ridges are often used as management action points (MAP). For example, an evacuation order may be required if the fire approaches a given MAP.

Imagery Ortho-rectification

For the evaluation mission, the desired imagery positional accuracy of the imagery was to be within 2 pixels of the corresponding ground feature locations at nadir. Based on the previous engineering and operational flights of the WAI by Xiomas, this was not unreasonable. In comparison, ortho-rectified Phoenix imagery is typically within 1-2 pixels of corresponding ground feature locations at the nadir of the imagery strip.

Overall the ortho-rectification of the mosaics was generally very good regardless of flight line direction, North-South or East-West, when compared to the 2011 Idaho NAIP with one exception. RSAC staff found a persistent shift between individual mosaic frames on one of the fires, Pine Creek, which was flown East-West, and this shift occurred on both days that the fire was flown (figure 5). This shift was not apparent on the other fires flown with the WAI during the evaluation mission, but that may be due in part to a lack of prominent cultural features (e.g., roads) in the vicinity of the Leggit, Ridge, and Summit fires. On these fires, geographic features such as lakes and stream drainages were used to evaluate the ortho-rectified mosaics. Xiomas attributed the shift, which was up to 10 meters, to some unique optical parameters in the WAI system that are not being accounted for in the current bore sight calibration procedure and a synchronization issue between the WAI camera trigger and the Applanix Position Orientation System (POS). Some of the shift may have been due to the bore sight calibration parameters used in the July 12 calibration mission not having a high degree of precision. Xiomas intends to address the frame mis-registration issue by refining the bore sight procedure; i.e., by refining the WAI optical parameters and developing a bore sight calibration procedure that can be run in the field. Xiomas also intends to improve the synchronization between the Applanix POS and the WAI camera trigger. The current system uses an interpolation of POS data to derive a position/orientation solution for the WAI camera trigger. Xiomas feels that direct triggering of the POS and the WAI camera using the Applanix software will produce a better solution.

Utility for Fire Mapping Products

When the Phoenix interpreted vector layers were overlaid on the WAI thermal mosaics, it was apparent that a very similar set of interpreted products could be readily derived using the WAI

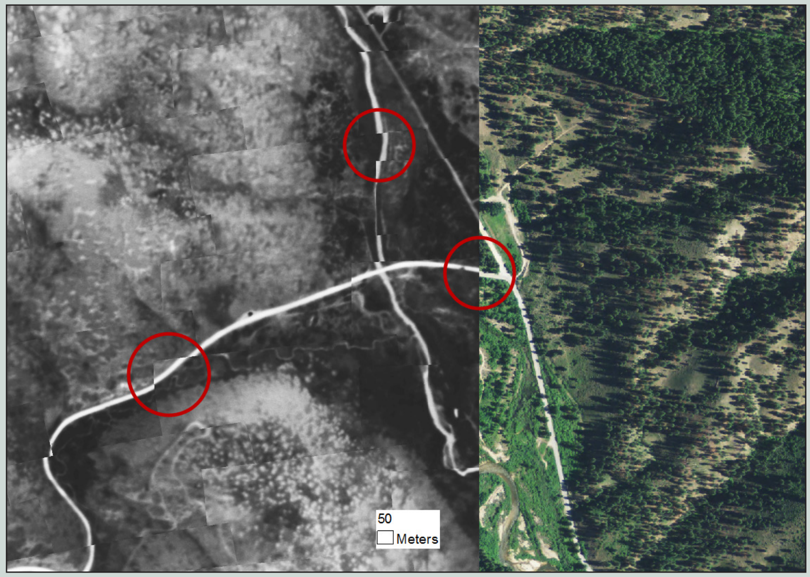

Figure 6—The positional shifting of individual WAI images relative to each other within the mosaic *(left)* and relative to the 2011 NAIP imagery *(right)* on the Pine Creek Fire is shown by the red circles in the figure. Note that individual trees, upland and riparian vegetation communities, roads, hydrography and terrain features are discernible from the thermal imagery.

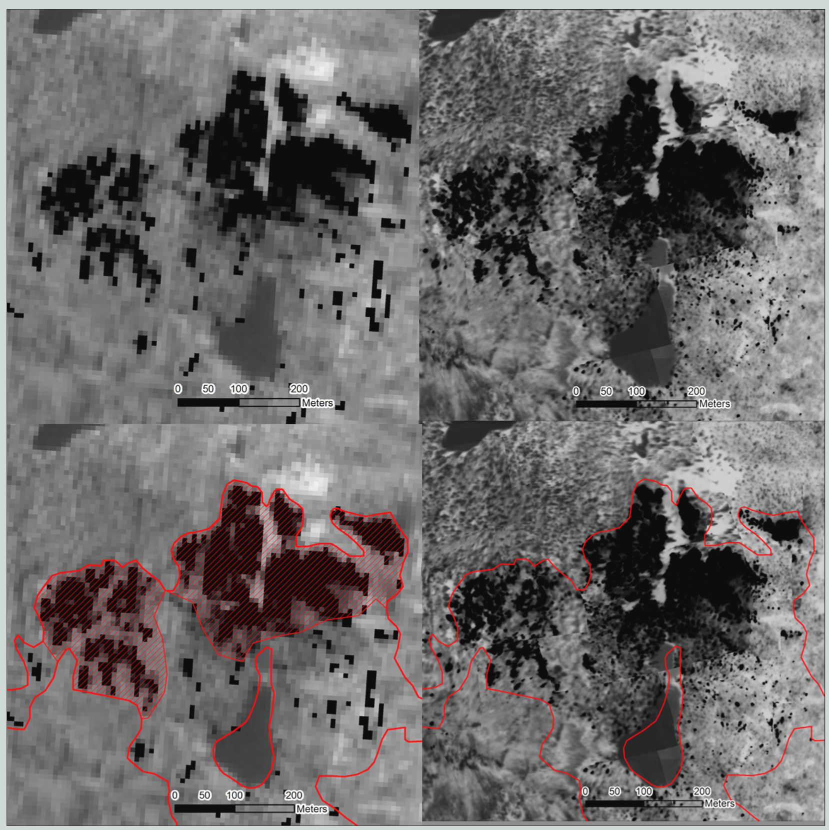

Figure 7—Phoenix LWIR thermal imagery *(upper, lower left)* and WAI LWIR thermal imagery *(upper, lower right)* of the northern portion of the Ridge Fire acquired on July 24, 2013. Although WAI thermal imagery is acquired as “white is hot”, both sets of imagery are displayed in figures 7–9 as “black is hot” for ease of comparison. Red polygons derived from the Phoenix imagery represent the fire perimeter *(unfilled)* and areas of intense heat *(hatched)*. Although the level of detail would be different, a very similar product could be interpreted from the WAI imagery.

imagery (figure 7). However, given the flight specifications and sensor configurations for this evaluation mission, a much more detailed perimeter could be derived from the higher-resolution WAI imagery (0.66 meters) than from the Phoenix imagery (3.5 meters).

A visual assessment of the fire detection layer output from the WAI MWIR/LWIR ratio algorithm showed it to be similar in distribution to the fire detection layer produced by the Phoenix system (figure 8). There were no obvious fire activity “false positives” detected—e.g., hot rocks mapped as active heat sources—in any of the output fire layers from the WAI. Additional review of the imagery demonstrated that the WAI data can be used to reliably differentiate other types of thermal features and anomalies (figure 9). This capability can be leveraged to enhance Forest Service resource mapping applications and address additional information needs.

Comparing the respective Phoenix and WAI fire detection output products was problematic. With the WAI system, the MWIR/LWIR ratio threshold was set prior to acquiring imagery of a given fire. With the Phoenix system, the MWIR/LWIR ratio algorithm threshold is routinely adjusted by the operator during imagery acquisition for a given fire. The difference in the distribution and total number of WAI fire layer pixels compared to the Phoenix fire layer pixels shown in figure 8 for the Ridge Fire is a result of the difference in the respective technician-set thresholds, and the difference in spatial resolution of the respective systems, which could not be fully captured and normalized in this exercise.

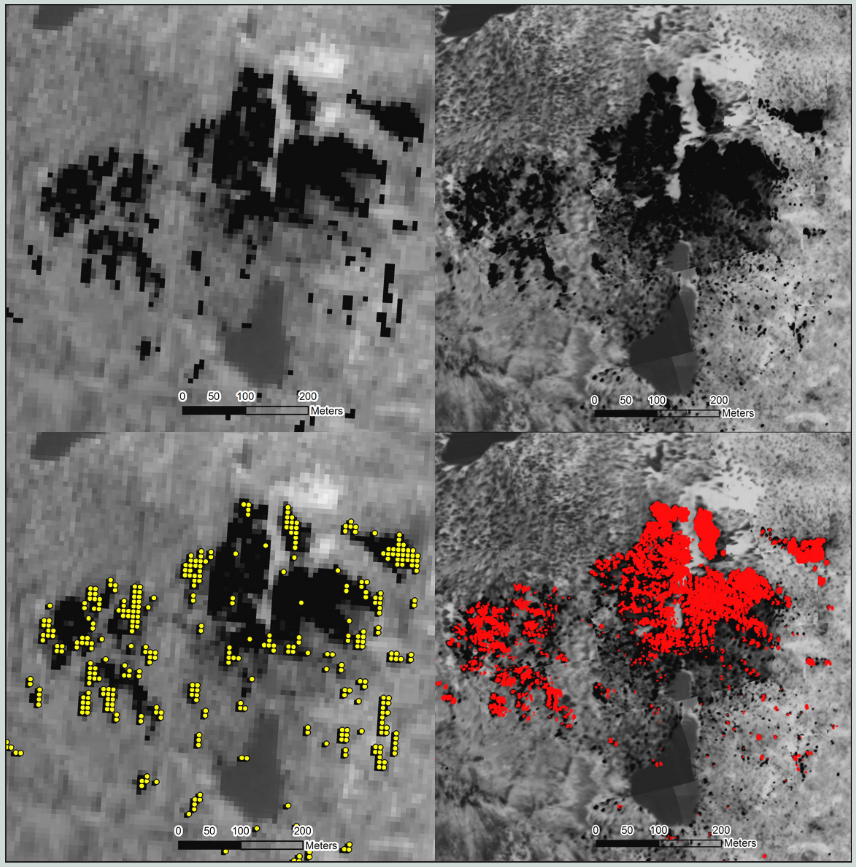

Figure 8–Phoenix *(upper left)* and WAI *(upper right)* LWIR imagery and corresponding fire detection output layers *(Phoenix lower left, WAI lower right)* for the Ridge Fire, acquired on July 24, 2013. For both images, dark pixels are hotter. Red in the WAI, represents pixels for which the MWIR/LWIR ratios exceeded a threshold set by the technician and are interpreted as active fire. Yellow points in the Phoenix graphic are the vector representation of the active fire pixels. The difference in the coverage of active fire pixels in the Phoenix and WAI outputs is due to the use of different thresholds.

Further examination of the WAI fire detection data by the RSAC staff revealed that some single isolated heat sources in the imagery mosaics were represented as multiple detections in the derived fire detection layer (figure 10). Xiomas attributed this to a combination of image mis-registration and frame-to-frame overlap between and within the flight lines.

Discussion and Recommendations

Overall, the demonstration of the WAI prototype was successful and supports the conclusion that its use could allow the Forest Service to conduct tactical fire imaging activities more cost-effectively and safely than with present systems. For example, the greater swath width afforded by the sensor at a higher flight altitude will facilitate faster imaging of a fire at nearly the same spatial resolution as the Phoenix system and consequently reduce fuel costs and flight times. However, the RSAC staff identified several items that need to be addressed, both in the context of this evaluation and beyond, to make it a system that can be used for operational NIROPS support.

RSAC staff found the integrated WAI system (infrared sensor, Applanix INS/IMU, image processing software, etc.) capable of acquiring, ortho-rectifying, and mosaicking thermal imagery in flight. The image processing software successfully generated derivative fire detection layers from the mid- and long-wave thermal imagery. To enable it to function as a fully operational NIROPS support asset, the WAI system would need to be integrated with an AirCell telecommunications system to deliver imagery and derived products in near real-time. Additionally, AirCell integration would allow for remote control operation of the sensor system which would eliminate the need for a system operator on the aircraft. The WAI software would also have to be modified to facilitate this capability. Finally, as a precaution and for system longevity, the WAI system components need to be hardened (better shielding on power supplies and cables, upgraded computer boards, etc.) to improve overall system reliability.

As part of the evaluation, RSAC closely assessed near contemporaneous imagery and derived systematic and interpreted products from the WAI and Phoenix systems. Based on this assessment, it is estimated that the WAI could at a minimum, provide operational continuity in tactical fire mapping capabilities by the Forest Service.

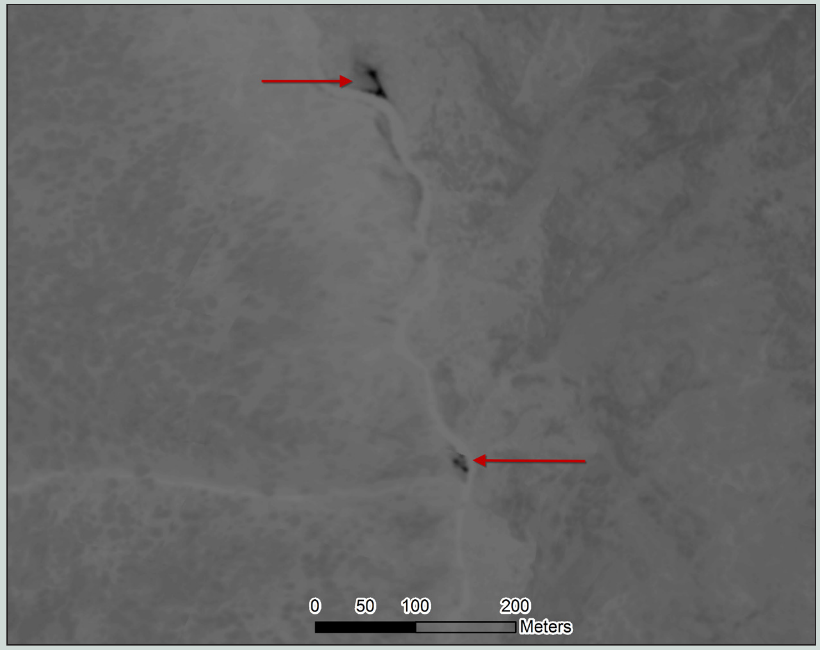

Figure 9—WAI LWIR imagery acquired on July 24, 2013 showing two apparent heat sources near the Ridge Fire that did not exceed the MWIR/LWIR ratio algorithm threshold. Further investigation revealed that the upper source was a gravel bar adjacent to the stream and the lower one was a hot spring in the stream channel.

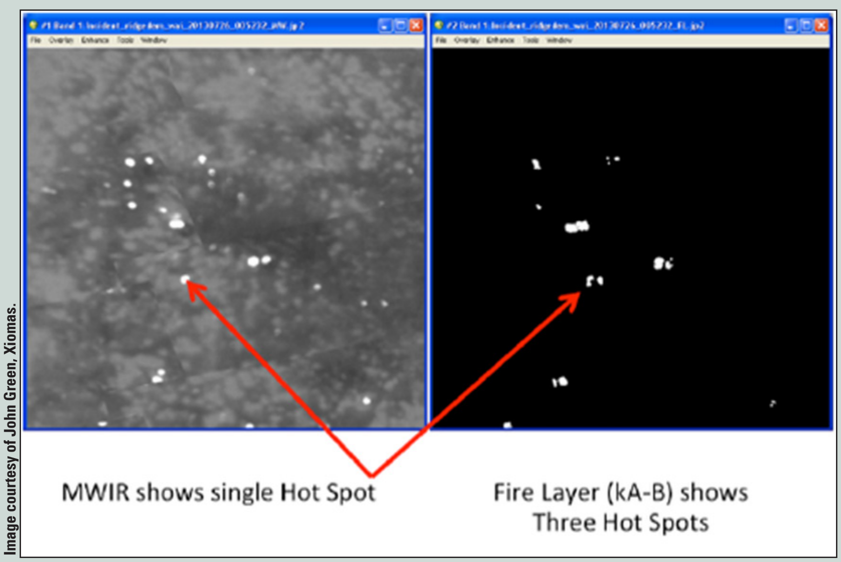

Image courtesy of John Green, Xiomas.

Figure 10—Isolated heat sources *(white)* in the WAI MWIR imagery *(left image)* are output in the fire layer as multiple heat sources *(right image).* Due to sidelap and endlap of individual imagery frames in the imagery mosaic, multiple looks at isolated heat sources were portrayed as multiple heat sources in the WAI fire layer output.

However, imagery mosaics for the Pine Creek Fire were mis-registered beyond an acceptable tolerance for NIROPS operations. Additionally, close evaluation of the WAI fire detection layer identified some multiple, or duplicated hot spots for a single actual detection. Xiomas indicated that these particular issues can be corrected by refining the overall bore sight calibration process and developing a field bore sight calibration process. Currently, the bore sight calibration requires the imagery and INS/IMU data to be sent to a vendor for processing and evaluation. Xiomas also will improve the integration and synchronization between the Applanix INS/IMU and the WAI camera system to further minimize mis-registration of output imagery and its effects on derivative products.

Due to a malfunction in the WAI CIR camera that could not be diagnosed or corrected prior to the evaluation mission, VNIR imagery could not be evaluated. Availability of a combined VNIR/MWIR/LWIR system for future NIROPS operations will address the increasing need for daytime fire intelligence information on active wildfires and support post-fire severity/damage assessments. Xiomas indicated that they can replace the current CIR camera with one from a different vendor and improve the camera interface for a more reliable system. If this occurs, RSAC would support conducting a daytime fire mapping mission over suitable wildfires and post-fire burned areas with the CIR and daytime thermal imagery being sent to RSAC for evaluation.

Conclusion

Our evaluation, as described in this report, indicates that the WAI has the potential to provide operational continuity in tactical fire mapping capabilities by the Forest Service. It also has the potential to do so more safely and at a reduced cost than the current sensor system.

Implementation of recommended system refinements will increase the capability and reliability of the WAI and elevate it to a higher TRL. With the provision by the Forest Service of an appropriate aircraft platform, AirCell system and related technical investments, the WAI would be considered a suitable operational system to support the NIROPS program and other resource mapping programs of the agency.

For additional information, contact:

Brad Quayle, RDAS Program Leader
Rapid Disturbance Assessment & Services
Remote Sensing Applications Center
2222 West 2300 South
Salt Lake City, UT 84119

phone: (801) 975-3737
e-mail: bquayle@fs.fed.us

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