Evaluation and use of remotely-piloted aircraft systems for operations and research—RxCADRE 2012

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Abstract

Small remotely-piloted aircraft systems (RPAS), also known as unmanned aircraft systems (UAS), are expected to have important contributions to wildland fire operations and research, but their evaluation and use have been limited. Our objectives were to leverage US Air

Force (USAF) controlled airspace to (1) deploy RPAS in support of the 2012 Prescribed Fire Combustion and Atmospheric Dynamics Research (RxCADRE) objectives including fire progression at multiple scales, and (2) assess tactical deployment of multiple RPAS with manned flights in support of incident management. We report here on planning for the missions, including the logistics of integrating RPAS into a complex operations environment, specifications of the aircraft and their measurements, execution of the missions, and considerations for future missions. RPAS deployed ranged both in time aloft and in size, from the Aeryon Scout quadcopter to the fixed wing G2R and ScanEagle. Real-time video feeds to Incident Command staff supported prescribed fire operations, and a concept of operations (a planning exercise) was implemented and evaluated for fires in large and small burn blocks. RPAS measurements included visible and longwave infrared (LWIR) imagery, black carbon, air temperature, relative humidity, and three-dimensional wind speed and direction (see application in Dickinson et al, *this issue*).

Additional keywords: Remotely-piloted Aircraft Systems, RPAS, Unmanned Aircraft Systems, UAS, Concept of Operations, CONOPS, remote sensing, G2R, ScanEagle, fixed-wing aircraft, Aeryon Scout, rotor aircraft, vertical takeoff and landing, thermal imagery, three dimensional wind, black carbon.

Summary

Remotely-piloted aircraft systems (also known as unmanned aircraft systems) were integrated into a complex operations environment including piloted aircraft to meet wildland fire research

objectives and assess their use in supporting prescribed fire operations. US Air Force safety protocols formed the basis for mission planning.

Introduction

The use of piloted aircraft to collect infrared, visible, and other passive imagery and active data such as light detection and ranging (LiDAR) have long been recognized as critical for wildland fire research and all-risk (e.g. wildfire, hurricane, earthquake) emergency response (e.g. Kremens *et al.* 2010, Francis 2012). Small remotely-piloted aircraft systems (RPAS), also known as unmanned aircraft systems (UAS), are expected to have advantages over piloted aircraft for monotonous, dangerous, and “dirty” (e.g. smoke-obscured) missions (Ambrosia and Wegener 2009). In the context of wildland fire research, missions suited to RPAS might include flights through smoke plumes; long-term loitering over prescribed-fire burn blocks or portions of wildfires; and rapid access to remote parts of wildfires where measurements are being conducted and fuel treatments have been installed. From a prescribed fire operations perspective, RPAS may provide a means of obtaining continuous information on the behavior of large prescribed fires for use in guiding ignition operations and on three-dimensional wind fields upstream of fires. For wildfire operations, RPAS may provide imagery during nighttime and smoky conditions that prevent operation of piloted aircraft and might be used for over-the-hill fire observation.

Despite their promise, deployment of small RPAS in wildland fire operations and research has been evaluated only under limited circumstances (Ambrosia and Zajkowski 2012), in part because of limitations imposed by Federal Aviation Administration (FAA) regulations and a lack of standard protocols for operations near manned aircraft (Rango and Laliberte 2010).

Eglin Air Force Base's (EAFB's) controlled airspace and robust prescribed burning program offer a unique opportunity to the wildland fire community to both evaluate the performance of RPAS in data acquisition and to develop and test standard operating procedures for the concurrent use of RPAS and manned aircraft during wildland fire operations and research. We used the Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE) 2012 campaign as a focal point for developing and evaluating a concept of operations (CONOPS) that would deploy RPAS along with piloted aircraft for operations and research objectives.

The first deployment of small RPAS on wildland fires on EAFB occurred during the 2011 RxCADRE field campaign where the Aeroviroment Raven, Peoria Maveric, and G2R RPAS were flown over a forested block after ignition by a rotor-wing, piloted aircraft to test real-time infrared imaging, downlink, and display. The RxCADRE 2012 campaign, funded by the Joint Fire Science Program, offered an opportunity to make simultaneous measurements with both RPAS and piloted aircraft on fires in (1) large blocks such as would be burned routinely as part of EAFB's fire management program and for which smoke plume development, chemistry, and transport were a focus, and (2) small blocks with relatively simple fuels for which perimeter development and flame front characteristics were of primary interest. As a means of safely managing a complex series of activities involving multiple aircraft and on-the-ground operations and research personnel, prescribed fires were organized as individual incidents within the National Wildfire Coordinating Group's Incident Command System, each with its own incident action plan. RPAS operations were primarily a collaboration between EAFB (the Natural Resource Branch "Jackson Guard" and the 96th Test Support Squadron [96 TSSQ]); the US

Forest Service, Remote Sensing Application Center and Research and Development); University of Alaska; San José State University; and the US Environmental Protection Agency.

The objectives of the 2012 CONOPS evaluation can be divided into operations and research. Operations objectives focused on (1) testing the integration of multiple small RPAS and piloted aircraft into wildland fire incident management using military safety protocols to provide intelligence data to incident commanders, (2) using software developed by the US Air Force (USAF) to display real-time georeferenced data for incident staff from multiple RPAS showing evolution of flame fronts, wind-speed and direction of smoke transport, and the location of fireline personnel, and (3) evaluating a variety of RPAS for their tactical value to wildland fire incident management. Primary research objectives for small RPAS were to (1) provide longwave infrared (LWIR) and visible imagery of developing patterns of fire spread at both synoptic and local scales for evaluating fire models on small blocks; (2) provide LWIR imagery of fire spread through clusters of instruments in and around 20 m $\times$ 20 m highly-instrumented plots (HIPs) on large blocks; and (3) use loitering patterns and continuous measurements to acquire LWIR and visible imagery and temperature, relative humidity, and select smoke plume data in association with airborne imagery and tower-based measurements on large blocks. Testing in the 2012 RxCADRE burns focused on three RPAS platforms—the Aeryon Lab's Inc. Scout quadcopter and the G2R and ScanEagle fixed-wing aircraft (in increasing order by size and flight duration)—and image orthorectification and integration capabilities under development by the 96th TSSQ Digital Video Laboratory (DVL) Project Office using the TerraSight software package. The TerraSight software is a product of SRI International.

In this paper, we describe the RPAS, the sensors deployed on them, and their use; planning undertaken to integrate RPAS into RxCADRE 2012 prescribed fire operations; the execution of the incidents; and an assessment of successes, failures, and needed improvements.

Operations environment

The RxCADRE 2012 campaign involved two large blocks with herbaceous and shrub fuels, one large block with forested fuels, and six small blocks (100 m × 200 m) with herbaceous and shrub fuels all located on Range B-70 on the western side of EAFB. Large units (>100 ha) and small units (2 ha) required their own CONOPS because of differing research objectives focused solely on finer scale fuel conditions, micrometeorology and fire behavior. Eglin Air Force Base covers more than 186 000 ha, and much of this area is dedicated to weapons testing and live-fire military exercises. Most of EAFB is managed for fire-dependent longleaf pine savanna with prescribed fire applied on a 1- to 4-year rotation (see Ottmar et al, *this issue*). Range B-70 was chosen for the RxCADRE because the presence of nonforested and forested sites in close proximity supported research objectives. Figs. 1 and 2 show the layout of the blocks including instrument locations.

Flight hazards included a 30 m meteorological tower and a 25 m boom lift that elevated a FLIR camera (see O'Brien *et al. this issue*). In addition to these fixed towers, the US Environmental Protection Agency deployed a tethered aerosonde up to heights of 350 m to measure smoke density and chemical composition. The RPAS pilots were given the positions of these potential hazards before each sortie and modified RPAS flight plans as needed.

RPAS deployed during RxCADRE 2012

Three RPAS were used during the RxCADRE 2012 field campaign to provide a range of capabilities for evaluation (Ambrosia and Zajkowski 2012). RPAS included the relatively large catapult-launched ScanEagle (representing a long endurance system that could support large incidents), the hand-launched G2R (a hand-launched and belly-landing aircraft with moderate endurance), and the vertical takeoff and recovery Scout system (that must be operated by a crew in close proximity to the fire line). The aircraft are introduced in descending order of size and flight duration. Communication frequency information is shown in Table 1.

ScanEagle

Two ScanEagles (Fig. 3*a*) were used by RxCADRE to give synoptic overview for the large burns with a stabilized LWIR sensor. The ScanEagle was developed by Insitu, which is now a subsidiary of the Boeing Corporation, and is a widely used small RPAS first tested in 2002 and in continuous operational use since 2004. Designed for shipboard operations, it is launched by a catapult and recovered autonomously with a sky hook which is engaged by the ScanEagle's wingtip hooks. The ScanEagle uses both an onboard GPS and inertial measurement unit (IMU) to provide positional data. Specifications are provided in Table 2.

The ScanEagle is well suited for the synoptic overview mission because of the aircraft's performance characteristic and sensor specifications which allowed it to be on-station before the large burns were ignited and to stay on-station until the burn was completed. Oblique video imagery, both thermal and infrared, along with still image was collected for the two large burns (Fig.1). All imagery collected was managed through the TerraSight software package delivered by video feed to provide situational awareness for operations leads.

G2R

The G2R (Fig. 3*b*) collected visible and LWIR imagery and temperature, relative humidity, wind (speed and direction), and black carbon measurements over both large and small burns. Derived from the AeroVironment Pointer, the G2R has been upgraded by Advanced Research and Engineering Integration Solutions for the 96 TSSQ/RNXT Eglin AFB. These simple and robust RPAS are well suited for remote operations though hand launching and belly landing. Table 2 shows specifications.

The G2R deployed obliquely-oriented LWIR and visible cameras and a circular flight path to provide loitering (continuous) imagery of the entirety of small burn blocks during fires. For large blocks, loitering LWIR and visible imagery were collected as fires spread through HIPs on large burn blocks (Fig. 1). A range of measurements were collected at the HIPs, including pre- and postfire fuel samples (see Ottmar *et al.* this issue), fire radiation from nadir radiometers (see Hudak *et al.* this issue), and fire behavior (see Butler *et al.* this issue). In addition, meteorological data and black carbon measurements were collected with onboard sensors on one G2R that flew a racetrack pattern upwind of a meteorological tower positioned in or near each of the large burn blocks. All imagery collected was managed through the TerraSight software package delivered by video feed to provide situational awareness for operations leads.

Aeryon Scout

The Scout (Fig. 3*c*) was used to collect pre- and postfire natural color image mosaics, and to collect real time imagery over individual instruments on small blocks and over HIPs on large blocks (Fig. 1). The Scout is a commercial, off-the-shelf electric quadcopter with three sensors that can be rapidly interchanged (LWIR, color video, and high-resolution still). This RPAS is easily transported and operated by one person. The Scout's specifications are shown in Table 2.

The Scout was flown at least three times for the small burn units. It was used to collect pre- and postfire high resolution images of the burn units from which mosaics were generated During fires, the Scout was flown as low as 15.24 m AGL to take high resolution LWIR imagery of flame fronts spreading through instrumented areas. Because of limitations on time aloft, the Scout was operated near the fire line the flight crew was escorted by fire line qualified personnel.

Sensors deployed during RxCADRE 2012

The RPAS used several sensors based upon the scientific requirements of their mission. Sensors included: LWIR for flame-front description and progression mapping; natural color for characterizing pre- and postfire vegetation; meteorological for measuring air temperature, wind speed, wind direction (in three dimensions) and relative humidity; and particulate sensors for characterizing smoke. While the RPAS data have only been used in one study to date (Dickinson et al *this issue*), in keeping the RxCADRE goals, RPAS data are archived for wide distribution and use in future studies (U.S. Department of Agriculture, Forest Service 2014).

Thermal infrared

The G2R and Scout were equipped with TAU 640s which are a single-band, uncooled LWIR sensor made by FLIR. Similar instrument in bandwidth and resolution, the DRS-manufactured E6000 Thermal Weapons Sight was flown on the ScanEagle. The TAU 640 on the G2R was pointed at a fixed, oblique perspective from the left side of the aircraft. The field of view on the ground was then determined by maneuvering the aircraft vertically and laterally. The ScanEagle and Scout have their LWIR sensor mounted in a stabilized turret. TAU 640 specifications are shown in Table 2. The LWIR sensor on the ScanEagle was pointed obliquely (also to the left side of the aircraft) while the sensor on the Scout had a nadir perspective.

Infrared reference points were established to each plot to aid in orthorectification of LWIR imagery. The reference points were necessary because the LWIR sensors are subject to saturation when deployed to image wildland fires. Saturation is a situation where the radiation from very hot objects or heat sources overpowers the sensor, creating an image with low contrast (Zajkowski *et al.* 2011). Infrared references were coffee cans filled with burning charcoal briquettes, located and surveyed to reduce orthorectification error.

Visible

The G2R and the ScanEagle were equipped with visible cameras (Table 3) that captured imagery coincident with LWIR imagery. A future possibility is to create fused imagery with information from both sensors.

Image orthorectification and video feed

The Sarnoff TerraSight software package was used to orthorectify the G2R imagery. TerraSight uses the position data from the RPAS GPS, orientation information from the Internal Measurement Unit (IMU), manual control points, and a digital elevation model of the earth to create accurate orthrorecertified images. Data from all RPAS, except the Scout, were orthorecitfied in real time at the command trailer and made available to the incident management team. TerraSight uses attitude and position information along with the sensor metadata to project the image data on a map display. In addition, the imagery can be saved for additional analysis which can be done in near-real time, after the mission has been completed.

Meteorology and smoke

Both of the two G2Rs carried meteorology sensors and an aethalometer to measure smoke concentration (Table 4) in addition to the LWIR and visible cameras. An aethalometer measures the concentration of suspended particulates in the atmosphere. It was mounted on the nose of the G2R so that the aircraft induced turbulence would not affect the measurements. An aircraft icing warning sensor built by Airborne Innovations LLC was used to collect temperature and relatively humidity. Three dimensional wind direction and speed were calculated using the RPAS GPS and IMU data. These sensors were flown over both the large and small burns.

Planning for RPAS operations

Incident organization

Each prescribed fire was treated as a separate incident in accord with the National Wildfire Coordinating Group (NWCG) Incident Command System (Fig. 4). Each incident had its own incident action plan.

CONOPS

Current Federal Aviation Administration policy (FAA 7210.846, 8900.227) require public (i.e. government) operators to obtain a Certificate of Authorization before flying in the national airspace system (NAS), and as of now, flying multiple UAS in the same airspace in the NAS is not allowed. Military bases usually have restricted airspace so that they can train for missions safely and are responsible for all operations within the restricted area (14 CFR 73.15). Integration of RPAS access, both public and commercial operations into the NAS will require addition testing and evaluation once the FAA publishes regulations (Mulac 2011). By separating aircraft through location, altitude, and time, the RxCADRE test showed that RPAS can operate with manned aircraft over prescribed fires once a common set of operations rules have been established and briefed. The RxCADRE went through the standard Air Force safety review process with the EAFB Risk Management Board which included a comprehensive hazard analysis to ensure that the RPAS operations complied with all rules and regulations. This process, though developed at EAFB, could be integrated into any military restricted airspace with little modification.

While EAFB has used target drones and has flight tested military RPAS for decades, they have little experience with using RPAS to support environmental management. The 96th TSSQ used the RxCADRE to evaluate potential RPAS application in wildfires and to help develop RPAS CONOPS. The two scales of burn blocks used during RxCADRE 2012 on Range B-70, large and small, required separate CONOPS due to different mission objectives and suite of RPAS used.

The RPAS were based in a common staging area located about 5 km from the burn units. The staging area included the Digital Video Laboratory [DVL] Test and Analysis Capability (DTAC) support vehicle, which served as the coordination center for all RPAS and manned aircraft operations. The Research Branch Chief and the RPAS Project Engineer (Fig. 4) were based at the DTAC to monitor and manage all aerial operations. The DTAC also included the ground control station for both G2R RPAS. The ScanEagle ground control station was located in an adjacent, separate vehicle. The staging area served as the launch and recovery area for the

ScanEagle and G2R. As such, the equipment required for ScanEagle launch and recovery was located at the staging area.

Small burns CONOPS

Only small RPAS, not piloted aircraft, were used for monitoring fires in small burn blocks. The Scout was used to obtain pre- and post-fire color mosaics as well as detailed imagery around an 8.2 m tripod that elevated a nadir-viewing LWIR camera (see O'Brien *et al.* this issue). Due to battery limitations, two G2R RPAS were used so that the burn blocks would be imaged without gaps until the burnout was complete. This LWIR imagery was used to quantify fire progression (see Dickinson *et al.* this issue). Planning included development of a schedule for each burn (Table 5) and consideration of how RPAS flights would be coordinated to achieve research objectives and maintain 155 m of separation (Fig. 5). Separation between RPAS for the small burn was done by positioning the Scout near the burn block on the opposite side of the burn relative to the RPAS staging area (Fig. 6). When both G2Rs were operating over the burn they were separated by altitude and position in the orbit. In the event that one RPAS had to return to the staging area while the other was flying to the burn, two routes were plotted.

Large burns CONOPS

The large burn block CONOPS was far more complex due to the addition of manned aircraft, weather balloons, a tethersonde, and a 30-m tower managed alongside of four RPAS (Fig. 1, 7). The CSU-MAPS (California State University-Mobile Atmospheric Profiling System) meteorological tower was raised to 30 m and positioned interior of L1G and L2G (and was left at its position in L2G during the adjacent L2F burn). The GPS position of the tower was provided to the Research Branch Chief. All units received a common briefing and each unit received an air operations plan that detailed the mission. Radio communication was maintained between the manned aircraft and the DTAC which was in contact with the Incident Commander (Fig. 4). In addition to position reports given by the pilots the Research Branch Chief was able monitor to the real time position of the manned aircraft and RPAS through the Sarnoff TerraSight 3D Visualizer at the DTAC.

The DTAV was equipped with a TerraSight Ground Station which allowed the integration of real-time RPAS video imagery, RPAS and manned aircraft positions, and positions of flight hazards (e.g. the CSU-MAPS tower) to provide situational awareness for the research branch director. At any one time, live video from either the G2R or ScanEagle was displayed. Through integrating video imagery and aircraft positions, TerraSight provided a common operational picture (COP). In military and disaster response operations, the COP is a single identical display of relevant (operational) information shared by more than one part of the command and intended to improve situational awareness. In the case of RxCADRE operations, a single display was demonstrated

It is technically possible for this information to be provided to numerous locations including the manned aircraft and distributed ground personnel. If implemented correctly information provided by the 3D Visualizer or similar COP will give incident command teams the necessary situational awareness necessary to implement safe RPAS operations when used in conjunction with standard aviation CONOPS.

The overarching factor driving the large burn CONOPS was the safety of the manned aircraft crew. As with the small units, all aircraft were separated by time, location, and altitude (Table 6) (Fig. 7) and manned flights maintained communication with EAFB Air Traffic

Control. In addition, the airspace was restricted to all but RxCADRE aircraft. No RPAS overflight of manned aircraft was allowed and at least 305 m vertical separation was enforced if manned and RPAS were operating in the same area. The manned aircraft included a twin engine Piper Navajo, or high (altitude) manned (HM), that would make repeated passes over the block collecting LWIR imagery (Hudak *et al.* and Dickinson *et al.* this issue) and a Cessna 337, low (altitude) manned (LM), equipped with smoke sampling equipment (Strand *et al.* this issue). The smoke sampling mission required the Cessna to climb and descend during the burn event. The tree line surrounding the B-70 test range was used as a visual landmark to maintain lateral separation when the Cessna descended to near the altitudes at which the RPAS were operating.

Once the first weather balloon was launched, the ScanEagle and both manned aircraft would be launched (Table 6). The ScanEagle would then be positioned upwind of the burn unit while the LM would perform its vertical profile over the burn block. Once this maneuver was complete, the LM would fly down-wind of the burn block and the ScanEagle would be positioned over the burn. While this was taking place the HM would begin its orbit. The two G2Rs would then be launched and begin orbiting above their assigned HIPs and ignition operations would begin. Because of its battery limitations, the Scout would be launched only when the fire approached the HIP to which it was assigned.

While the ScanEagle had the endurance to fly for the entire burning period, the G2R that was launched first would have to return to base for battery exchange while the second G2R would launch and fly to the block to replace it (Fig. 6). The Scout was only flown while the fire was actively burning the assigned HIP. As soon as the burnout was complete, the ScanEagle would return to the upwind orbit until the LM had completed the final vertical profile and cleared the area. Once LM cleared the area, the ScanEagle was recovered and the second weather balloon was launched.

RPAS support for operations during RxCADRE 2012

The real-time LWIR video orthorectified by automated process with the TerraSight software and displayed for incident command staff provided unprecedented intelligence on how flame fronts were progressing and where igniters were in the burn block (based on inference from ignition patterns). Coupling LWIR video with GPS mapping of igniter positions would further improve situational awareness. As well, fusing LWIR and visible imagery may help in distinguishing levels of fire intensity that are obscured in highly saturated LWIR data. Three dimensional winds, collected by one of the G2Rs over large burns, might be a useful addition to the suite of information that RPAS can provide. Clearly, a balance must be struck between more information sources in the COP and the potential for too much information and resulting distraction.

Time aloft for the G2Rs was limited by battery life to 1.5 hours and was not long enough to encompass ignition operations and subsequent fire spread for typical prescribed burn operations (>500 ha) at EAFB much less many wildfire suppression operations. A hand-launched and belly-landing RPAS with longer duration would prove to be more useful in these situations. Such an aircraft would provide more operational flexibility and would remain relatively less costly than an aircraft like the ScanEagle.

Although saturated LWIR imagery from the G2R and ScanEagle are adequate for interpreting general fire progression (see Dickinson *et al.* this issue), the imagery provides limited information on fireline intensity. Saturation of the signal was expected because the LWIR cameras used were intended for providing information on low temperature objects like troops, not intensely radiating flame fronts. Quantitative radiant flux density (W m^{-2}) would be ideal, but even qualitative imagery with greater dynamic range would enable incident staff to better interpret fire behavior. A recent demonstration of “fused” LWIR (Tau 640) and visible (color) imagery from a G2R at EAFB shows promise in overcoming some of the limitations imposed by LWIR saturation in assessing (qualitative) fire intensity. The 2011 RxCADRE missions showed that is also possible that mid-wave infrared (MWIR) or short-wave infrared (SWIR) video would provide more useful information than LWIR. Clearly, more development is required on sensors and image analysis appropriate for wildland fire operations that will require dedicated laboratory and field testing. Regardless, operation objectives were far exceeded by the RxCADRE incident. The situational awareness provided by the TerraSight software package which handled data from up to five sources of aerial assets during the burn was unparalleled.

Research results from RxCADRE 2012

Analysis and research application of data from RPAS during RxCADRE 2012 has not been fully explored. At present, LWIR data from the TAU 640 camera flown on the G2R has been used in Dickinson *et al.* (this issue). To allow perimeter delineation, TerraSight was used to create georeferenced still images from the LWIR video with the aid of infrared targets and high resolution orthophotos. In contrast to operations support provided by real-time video feeds, research application of imagery required manual orthorectification to achieve sufficient accuracy for delineating fire perimeters. In addition to TerraSight, ESRI ArcMap, ERDAS Imagine, and AgiSoft were also used to create various example data products. All RPAS datasets discussed in this paper are available from the research archive (U.S. Department of Agriculture, Forest Service Research 2014).

Example data products

The ScanEagle orbited the large burn blocks at about 465 m AGL, obtaining oblique LWIR imagery at the same time as the piloted aircraft was collecting nadir LWIR imagery from passes every ~3 minutes from an altitude of more than 1860 m AGL. At its altitude and standoff distance, the field of view of the ScanEagle was slightly smaller than entire burn blocks (Fig. 8). Periodic frames from this dataset have been orthorectified and the data are currently being used for fire behavior model evaluation (Linn 2014).

The G2Rs were deployed for different purposes on large and small burn blocks. On large blocks, one was used to obtain visible and LWIR imagery of the fire passing through HIPs while the second was flown to obtain smoke particulate concentrations, three dimensional winds, and air temperature and relative humidity in proximity to the 30 m meteorological towers (though it also collected visible and LWIR imagery). An example image of fire spread near instruments in a large burn from the G2R's oblique LWIR dataset is shown in Fig. 9. Particulate concentrations and meteorological data are all referenced to time, latitude and longitude, and altitude from the G2Rs' onboard GPS and IMU. Particulate concentration data from the drum sampler aboard the second G2R are shown in Fig.10. On small burn block operations, a G2R orbited the units collecting oblique LWIR imagery. The imagery was used to delineate fire perimeters which were used in combination with quantitative data from tower-mounted radiometers to estimate fire radiated power (MW) over entire fires (see Dickinson *et al.* this issue). An example orthorectified false-color LWIR image from the G2R of a small burn block is shown in Fig. 11.

In addition to the focused monitoring of fire spread in a HIP, the Scout was flown opportunistically both before and during burns in large and small blocks (Fig 12). We had discussed flying the Scout above the center of the small units at an altitude sufficient to image entire 100 m × 200 m blocks during the fires. However, to achieve 155 m separation from the G2R and because of limits on flight time, we decided to use the Scout to image instrument locations during fire passage from near ground level. Arguably, using the Scout rather than the G2R to provide synoptic views of the block would have led to more successful orthorectification with the caveat that Scout flight time is severely limited.

Limitations and solutions

Standards for research data are higher than those for operations and, as such, certain limitations were encountered. First, consistent orthorectification of a time sequence of fire images was only obtainable for one fire and, then, only for images captured from the same perspective. A southerly perspective from 180 m AGL provided the best set of perimeters for small block S5 (see Dickinson *et al.* this issue). Because of the need to maintain perspective it was not possible to obtain useable images at a smaller time interval than 1 to 2 minutes. Hot infrared targets (burning charcoal pots) were helpful, but it was ultimately necessary to manually orthorectify images with additional reference to a high-resolution orthophoto. Contributing to the difficulty with orthorectification were likely image jitter and smearing from turbulence and a long exposure time, low resolution 3-D position data, and image blooming as a result of the use of an uncooled and saturated (low dynamic range) sensor.

A program to develop improved small RPAS sensors and methods for image orthorectification for fire research is needed (Laliberte and Rango 2011). It is not clear that small RPAS can soon replace piloted aircraft for high-quality, research-grade infrared imagery of wildland fires; however, there is substantial room for improvement in RPAS data. First, instruments with greater dynamic range are required. Second, experimentation with MWIR sensors may have merit, particularly in light of the existence of methods for extracting total radiant power from single-band data (e.g. Wooster *et al.* 2005, Kremens and Dickinson 2014). Short-wave infrared (SWIR) sensors may have merit for delineating flame fronts. Dual-band sensors would be even better in that they allow estimates to be made of total radiant power (Kremens *et al.* 2012). Methods for image calibration are critical, whether these involve on-board calibration, ground-calibration, or laboratory calibration coupled with fire pixel simulations (Kremens and Dickinson 2014). Third, orthorectification processes need to be improved for small RPAS data used in a research context. Improved LWIR image quality will certainly help (see above). Fusion of visible with infrared imagery, recently demonstrated at EAFB, may also help in that visible data are obtained at higher resolution and better lend themselves to automated orthorectification. At the present time, it is not clear that better RPAS 3-D positional data can be obtained given weight and cost limitations. As such, a certain amount of error, larger than error associated with imagery and other remote sensing products from piloted aircraft, may always be present. A nadir perspective would also aid in orthorectification though operational constraints prevented use of the Scout to obtain a synoptic view of the small blocks.

Conclusions

The RxCADRE 2012 campaign successfully demonstrated the use of RPAS as an operations-support tool. The RPAS flew over 50 sorties and provided real-time situational awareness to incident staff without major mishap. The implementation and testing of the CONOPS for joint manned and unmanned flights on large, operational-scale burns allowed each platform to operate without any major safety concerns. Frequency management is a critical element for RPAS operations, while secure, reliable Command and Control, and Data Link are critical for safe operations and data dissemination. The Scout showed the most promise for tactical deployments from remote locations near incidents, but each RPAS platform met objectives for the research and operations purposes for which it was deployed.

As data from RxCADRE 2012 RPAS are used for research studies (e.g. Dickinson *et al.*, this issue), more knowledge will be gained about the uses and limitations of the infrared and visible imagery and the meteorological data that were collected. Clearly, development of miniaturized infrared sensors deployable on small RPAS that provide more quantitative data is critical. As well, improved processes for orthorectifying imagery from small RPAS are required. We expect that RPAS data will ultimately show merit in supporting various RxCADRE research areas including fire behavior measurement, event-scale fire mapping, and emissions and event-scale plume behavior. A key area of interest is using RPAS to provide active fire data of higher spatial and temporal resolution (if reduced spatial extent) than can be obtained from manned aircraft and satellite sensors to better understand imagery from those sources.

The successful deployment of RPAS on both the 2011 and 2012 RxCADRE showed that RPAS are safe and robust tools for collecting scientific data over prescribed fires and for providing data for improving situational awareness for incident staff. Planning and coordination through an incident command structure is necessary to ensure safety and operational efficiency. Additional missions with RPAS on prescribed fires and wildfires will provide the necessary experience and data to support a greater role for RPAS in research and operations support.

Acknowledgements

We thank the Eglin Air Force Base prescribed fire staff for their high level of competence and willingness to support research operations. We also thank the many scientists and support staff not included in this paper whose work and collaboration made the RxCADRE project possible, particularly Roger Ottmar who led the effort and Dan Jimenez who facilitated agreements and funding. The 2012 RxCADRE campaign was made possible by grant #11-2-1-11 from the Joint Fire Science Program while longer-term support from the Department of Defense, US Forest Service, National Fire Plan, Joint Fire Science Program, and NASA were critical for getting the RxCADRE project started.

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TABLES

Table 1. Uplink and downlink frequencies for each of the UASs supporting this demonstration

UAS name	Command and control frequency	Video frequency
ScanEagle	1.37 GHz	2.4 GHz
G2R	351.35 and 365.25 MHz	2.2815,2.365,2.374, and 2.383 GHz
Aeryon Scout	2.4 GHz	WLAN 802.11 b/g

Table 2. Specifications of the RPAS used in this project

Specification	ScanEagle	G2R	Aeryon Scout
Length (m)	1.55	1.83	NA
Height (cm)	22		NA
Wingspan (m)	3.11	2.74	0.72[a]
MTOW (kg)	22	4	1.4
Endurance (hours)	>18	1.5	0.4
Cruise speed (m/s)	31	14	NA
Maximum speed (m/s)	41	21	NA
Wind tolerance (sustained/maximum) (m/s)			15/26

[a]From the top of one rotor to the tip of the opposite rotor.

Table 3. Infrared and visible camera specifications

Remotely Piloted Aircraft System	ScanEagle	G2R	Scout
Thermal sensor	DRS E6000	FLIR TAU 640	FLIR TAU 640
Lens (mm)	22	19	19
Array	640×480	640×512	640×512
Pixel pitch (μm)	25	17	17
Spectral bandpass (μm)	8–12	7.5–13.5	7.5–13.5
Sensitivity (NEdT)		<50 mK at f/1.0	<50 mK at f/1.0
FoV (degrees)	40°×30°	32°×26°	32°×26°
iFoV (mr)		0.895	0.895
Electro-optical sensor	Sony FCB-EX1000	Sony FCB-H11	VideoZoom10x
Lens (mm)		5.1–51.0	42–425
Array	380,000 pixels	1920X1080	
FoV (degrees)	57.8° (wide)–1.7° (tele)	50° (wide)–5.4° (tele)	50° (wide)–5° (tele)
Zoom optical	36×	12×	10×

Table 4. Specifications of the aethalometer used to make black carbon concentration measurements

Aethalometer make / model	AethLabs microAeth AE51
Measurement range	Avg. 100 µg BC m^{-3}@ 50 ml min^{-1}
Measurement resolution	0.001 µg BC m^{-3}
Measurement precision	±0. 1 µg BC m^{-3}, 1 min avg., 150 ml min^{-1} flow rate
Measurement time-based	1 min

Table 5. Planned operations schedule for example small burn block S7 on November 7, 2014

The G2R that was launched first is termed G2R1, while, as needed to relieve G2R1 because of battery limitations, the second G2R to be launched was termed G2R2. All times relative based on ignition time. Ignition was by hand and interior to the block on the upwind side.

Time (local)	Event
1050	Launch G2R1
1055	Launch Scout
1100	Ignition
	G2R1 orbits burn block at 180–200 m AGL
	Scout hovers at 15–30 m AGL above tripod
1115	Retrieve Scout
1120	Re-launch Scout (as needed/directed)
	Scout hovers at 15–30 m AGL above tripod or target of opportunity
1130	Launch G2R2
	G2R2 orbits burn block at 180-200 m AGL
1135	Retrieve G2R1
1140	Retrieve Scout
1200	Burnout complete
>1200	Retrieve G2R2

Table 6. Operations schedule for example large burn block L1G

The manned aircraft flying at low altitude for smoke sampling is termed LM, while the manned aircraft flying at high altitude for nadir burn block imaging is termed HM.

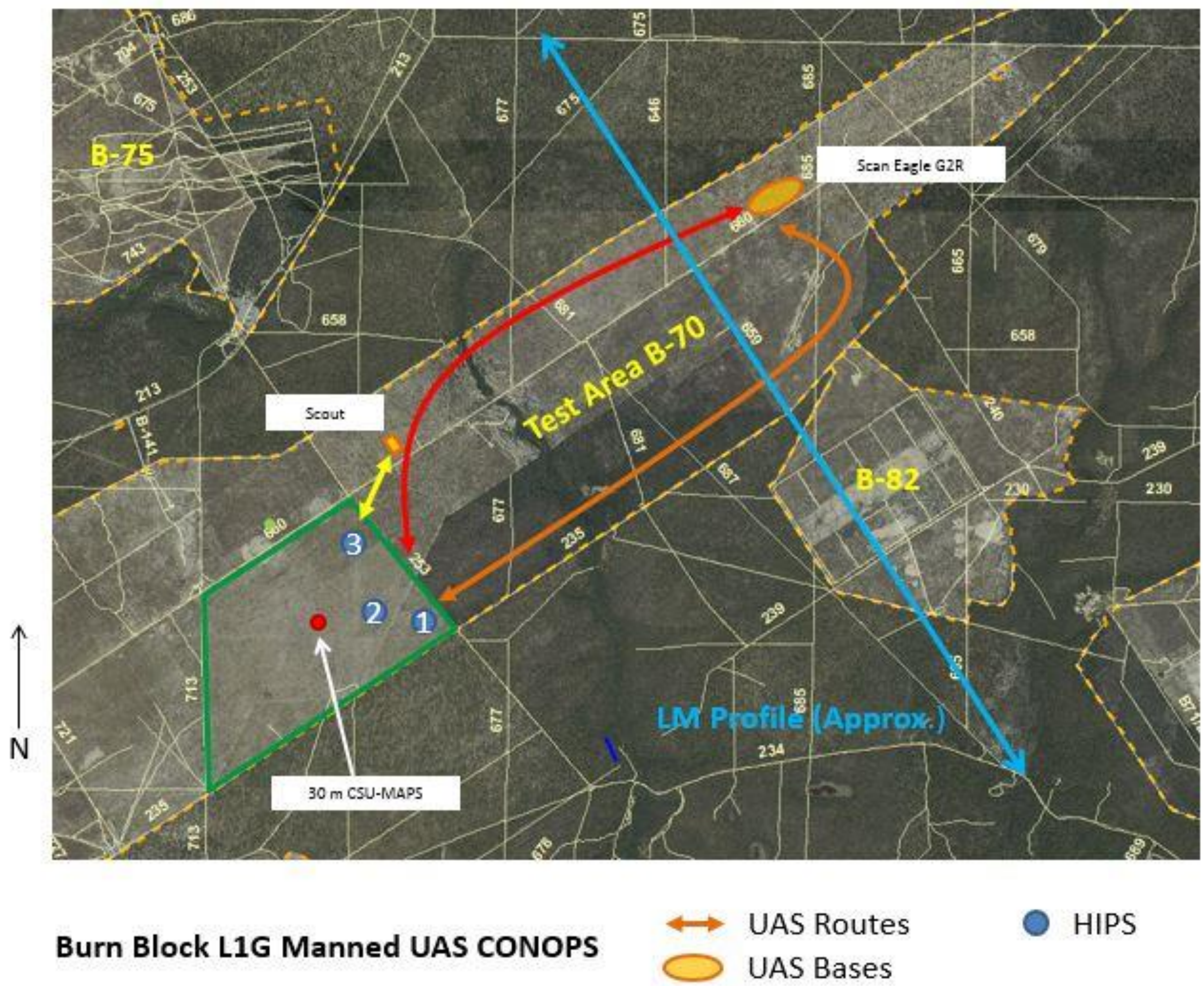
Time (local)	Event
1100	Launch weather balloon 1
1115	LM takeoff
1115	Launch ScanEagle
1130	LM begins sampling over burn block once ScanEagle is upwind of block
1130	HM takeoff
1145	Launch G2R1
1155	Launch G2R2
1200	Ignition and launch Scout
	LM cleared to fly downwind as desired
	HM makes passes 1200 m AGL over block for duration of burn
	ScanEagle orbits at 335 – 915 m AGL over block
	G2R1 and G2R2 orbit at 180–200 m AGL over HIPs 1 and 2 with 155 m lateral separation
	Scout hovers at 15 – 30 m AGL over HIP 3
1215	Retrieve G2R1 once LM confirms it is clear of Range B-70 (treeline) or is above 1800 m AGL
1215	Retrieve Scout
1220	LM cleared to profile as desired downwind of block

1230	Re-launch Scout (as needed/directed)
1230	Re-launch G2R1 once LM confirms it is clear of Range B-70 (tree line) or above 1800 m AGL
1230	Retrieve G2R2
1240	LM cleared to profile as desired downwind of block
1245	G2R1 on station, orbiting 180 m AGL over CSU-MAPS tower
1330	Burnout complete
	Retrieve ScanEagle once LM confirms it is clear of Range B-70 (tree line) or above 1800 m AGL
	Retrieve G2R1
	Release HM for landing
1430	Launch weather balloon 2
	Confirm LM is well clear downwind
	Confirm HM has departed Range B-70
	Confirm ScanEagle has landed

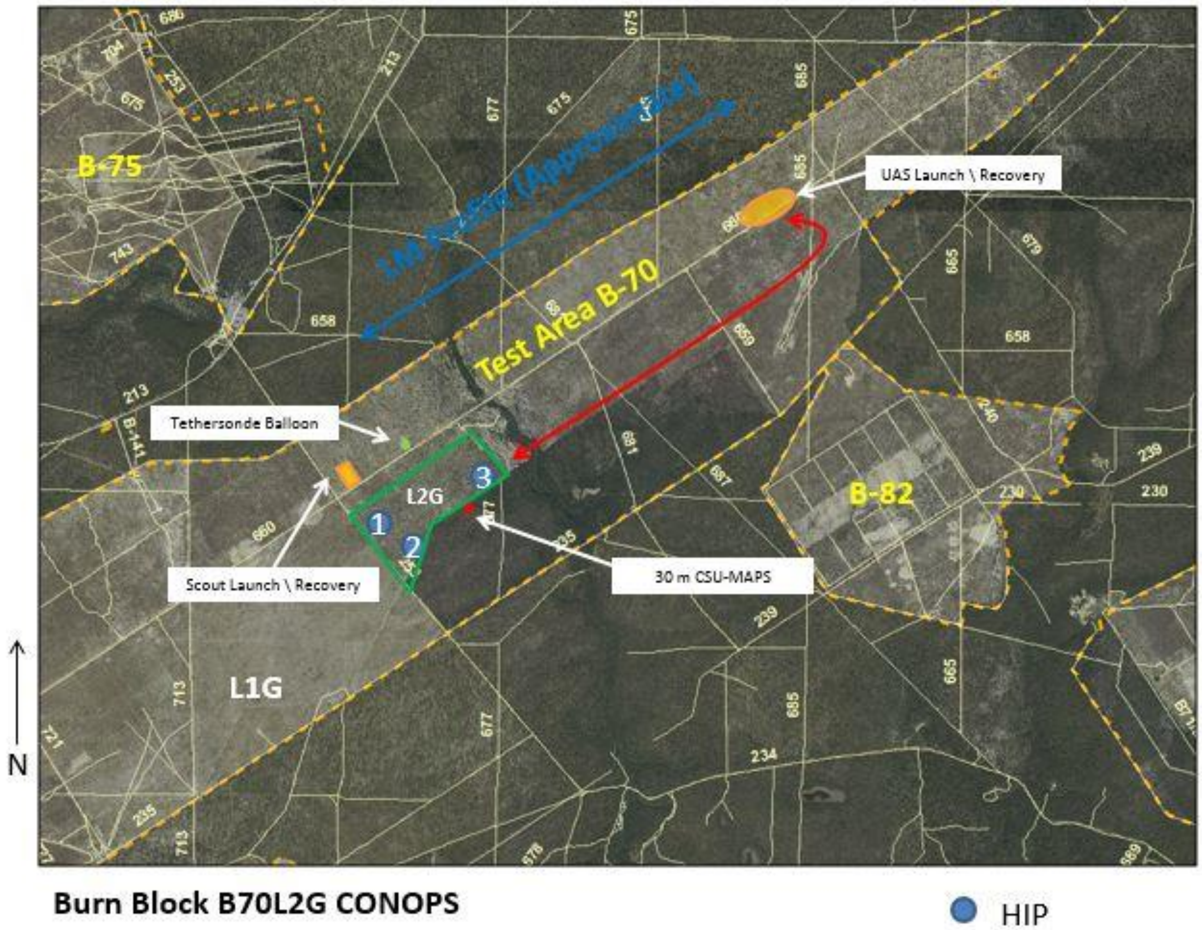
FIGURES

Fig. 1. Operational setting for large burn blocks. Note CSU-MAPS California State University Mobile Atmospheric Profiling System. Aircraft maintained a minimum of 155 m buffer (unmanned) 360 m (manned) from the tethersonde balloon.

L1G



L2G



B-75
Test Area B-70
UAS Launch \ Recovery
Tethersonde Balloon
L2G
1
2
3
Scout Launch \ Recovery
30 m CSU-MAPS
B-82
L1G
N
Burn Block B70L2G CONOPS
HIP

L2F

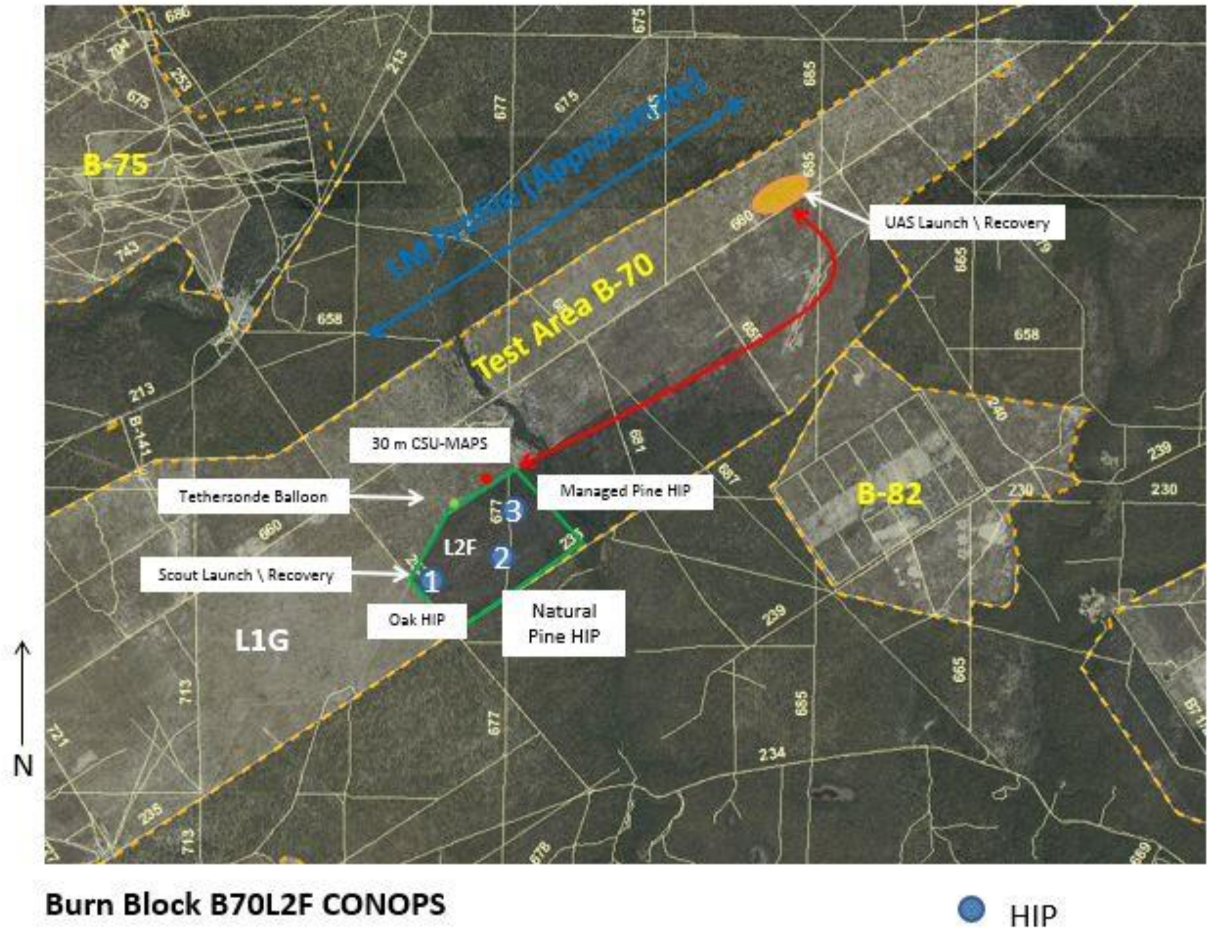


Fig. 2. Small burn block operational setting. Include boom lift relative location(s)

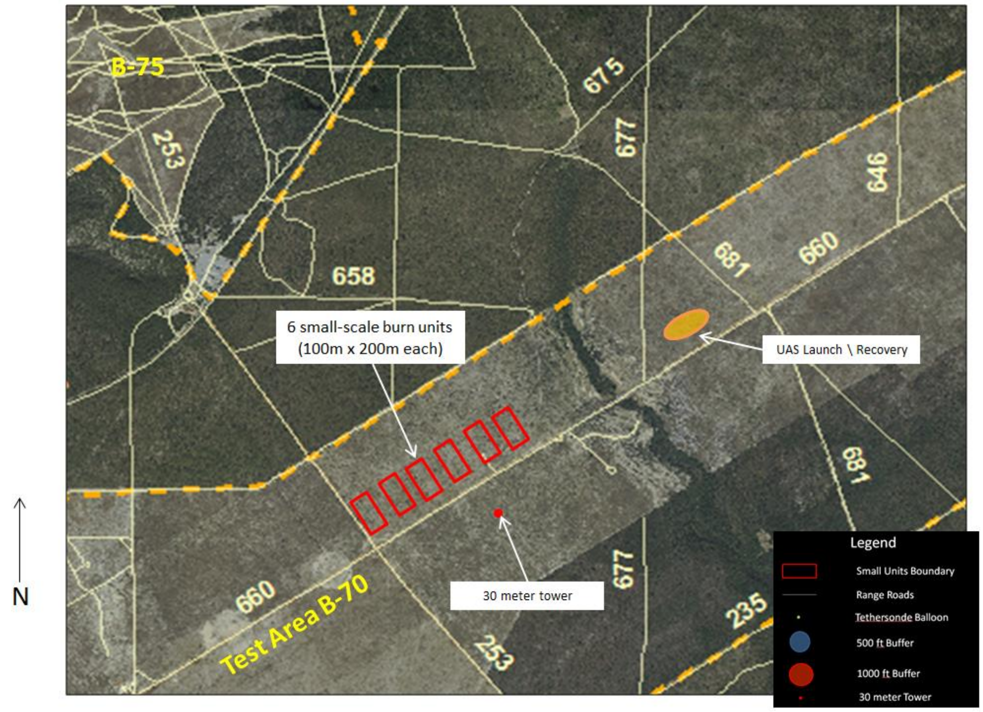


Fig. 3. RPAS used in the RxCADRE 2012 campaign.

(*a*) The ScanEagle image shows the catapult and SkyHook in the background. (*b*) The G2R is hand launched and lands on its belly. (*c*) The Scout takes off and lands vertically.

A.

B. ScanEagle

C. G2R

D. Aeryon Labs Scout

Fig. 4. Incident command communications structure.

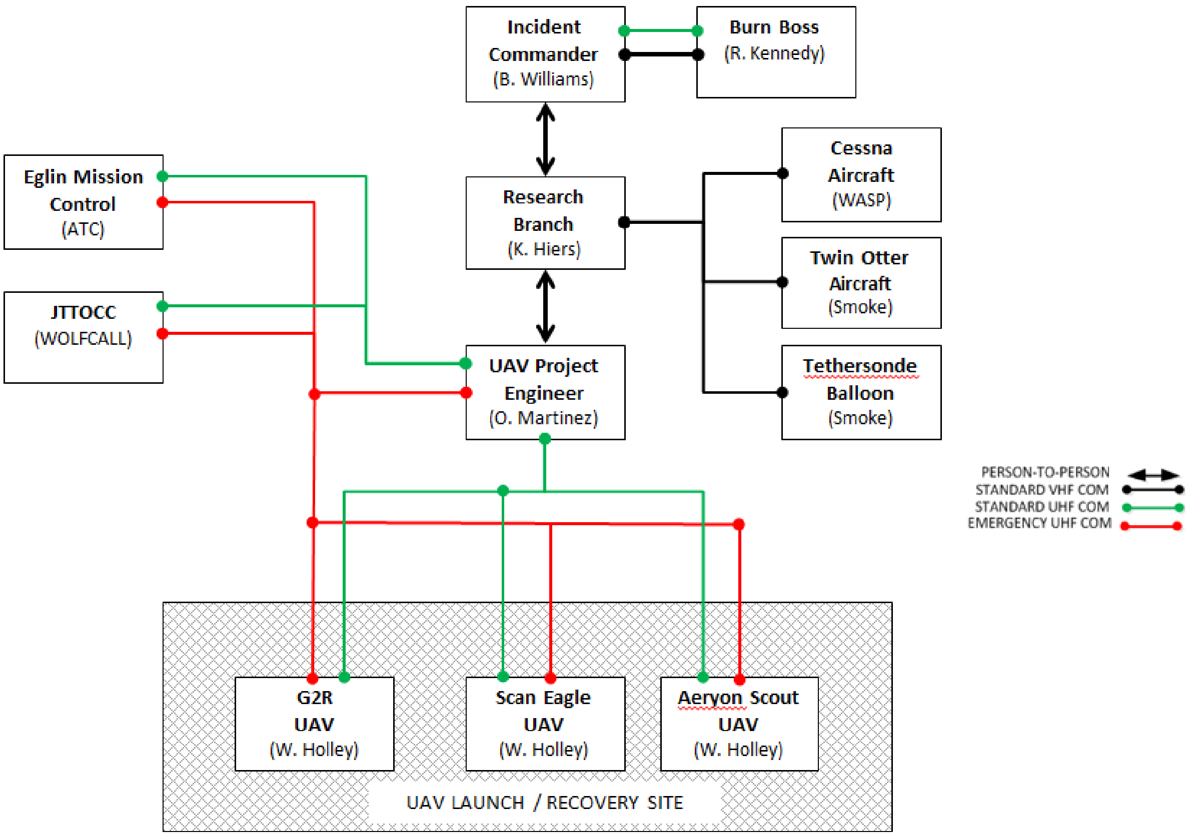
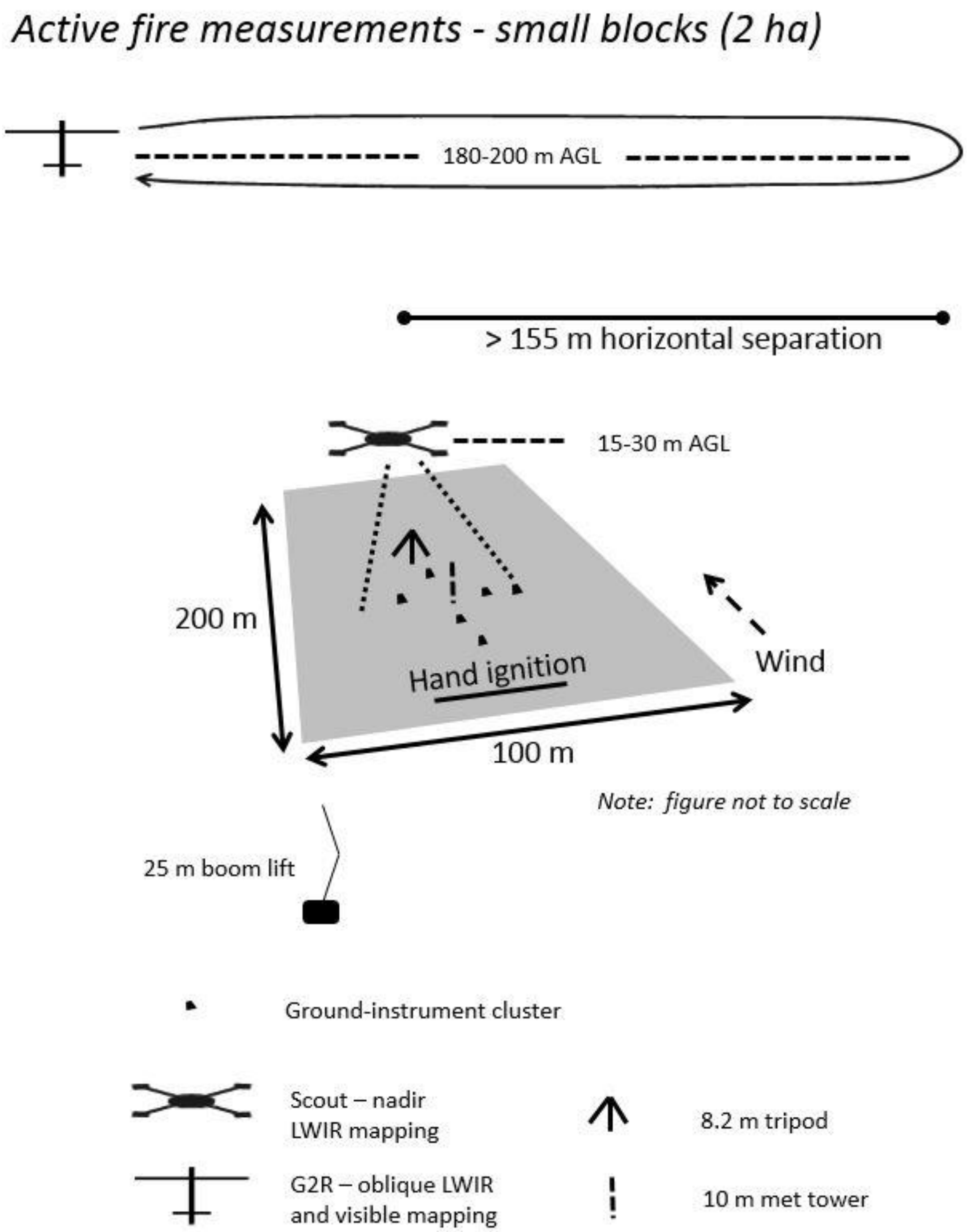


Fig. 5. Small burn block general flight coordination.



S

Fig. 6. Flight paths used to maintain separation among the three RPAS deployed during small block burns.

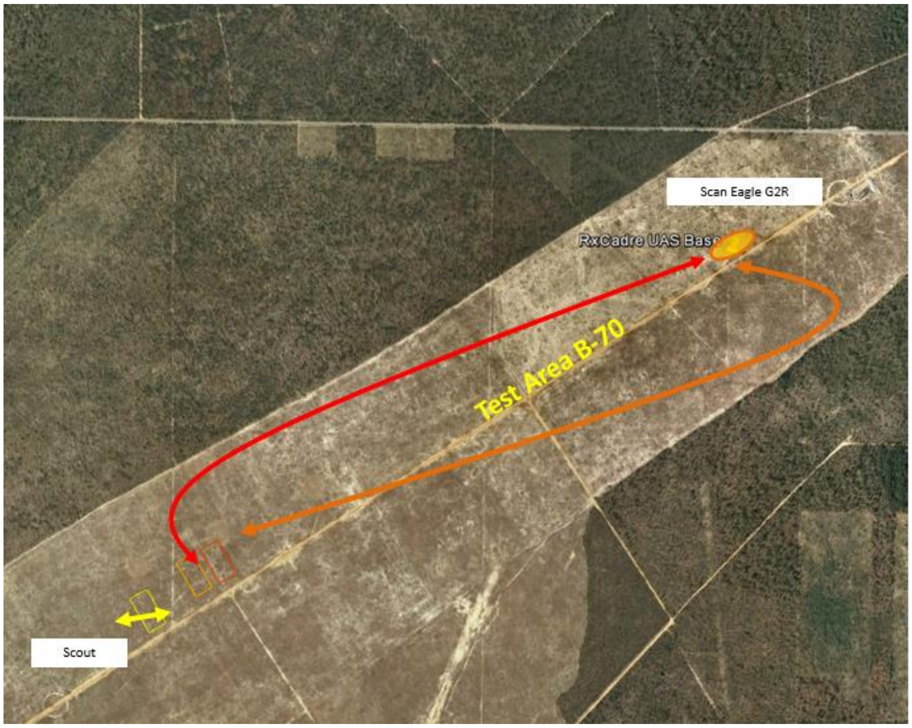


Fig. 7. Large burn block general flight coordination.

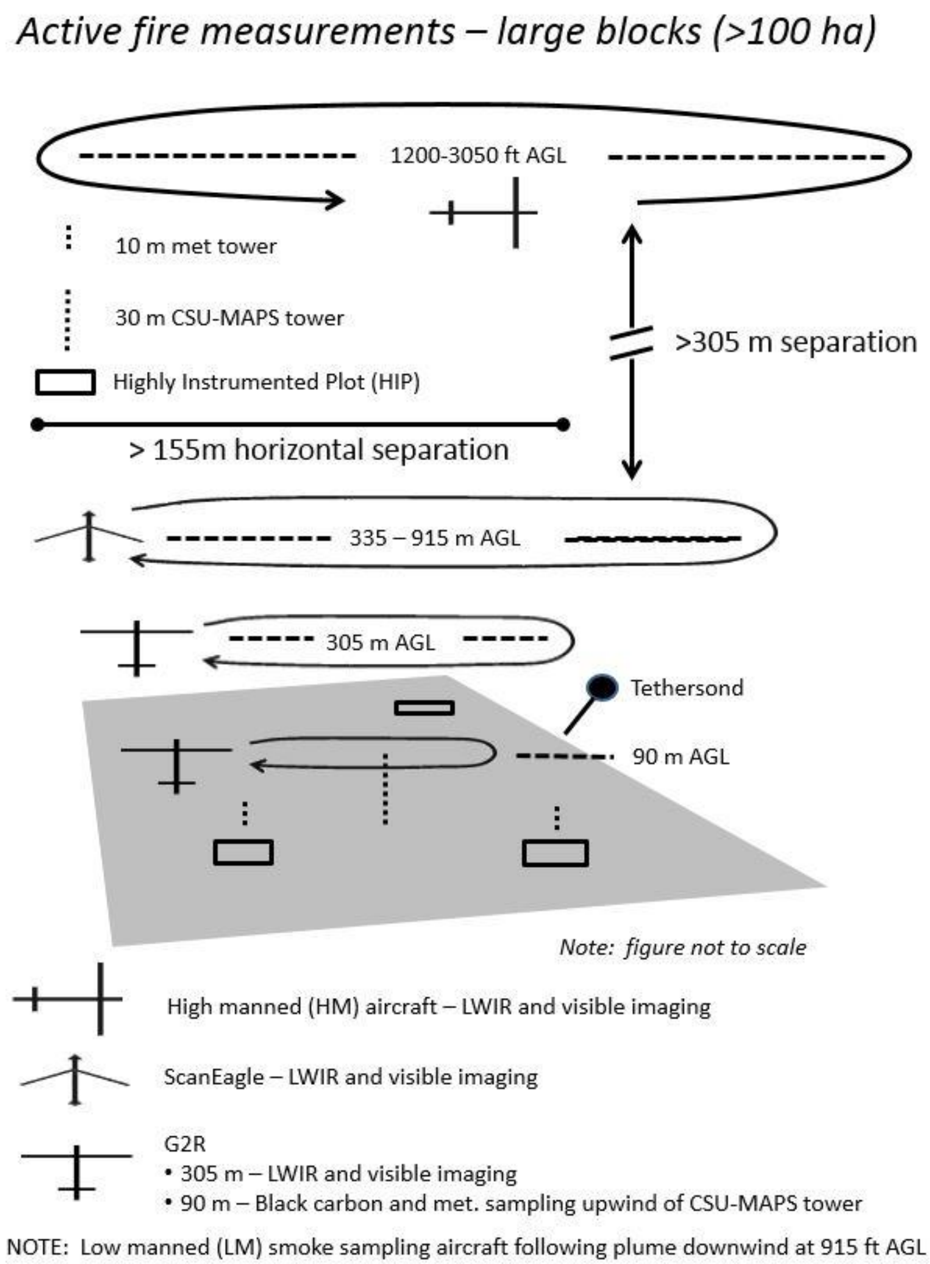


Fig. 8. ScanEagle oblique LWIR imagery of block L2G from a southeasterly perspective.

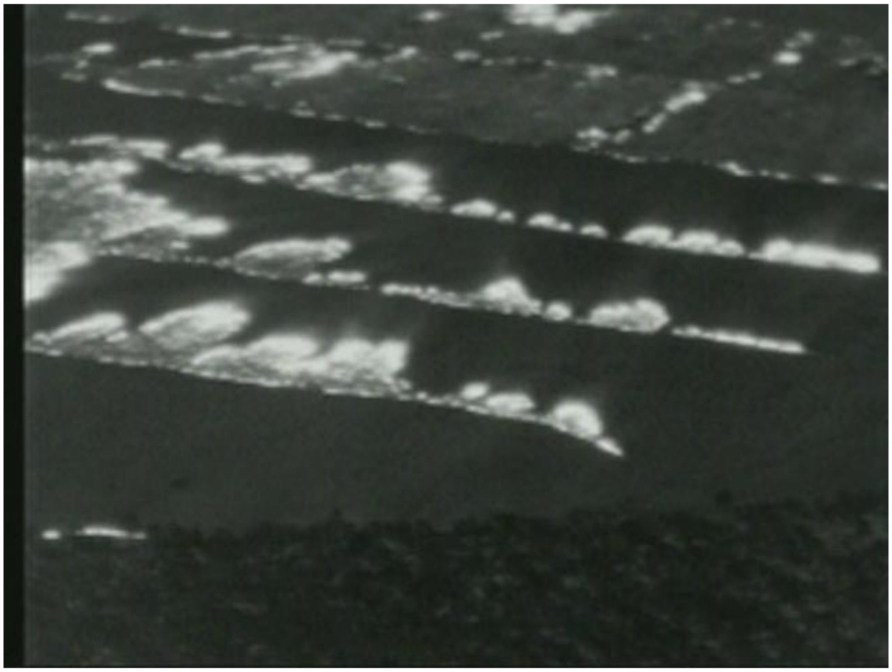


Fig. 9. Oblique LWIR image from the G2R as flames spread through a highly-instrumented plot. Visible in the image is the tripod elevating a nadir LWIR camera (O'Brien *et al.* this issue) and dual-band radiometer (Dickinson *et al.* this issue). This image is from large block L2F.

Fig. 10. Relative concentrations of black carbon particles over the S5 burn block. Data were collected from a G2R flown in a racetrack pattern upwind of a 30 m meteorological tower.

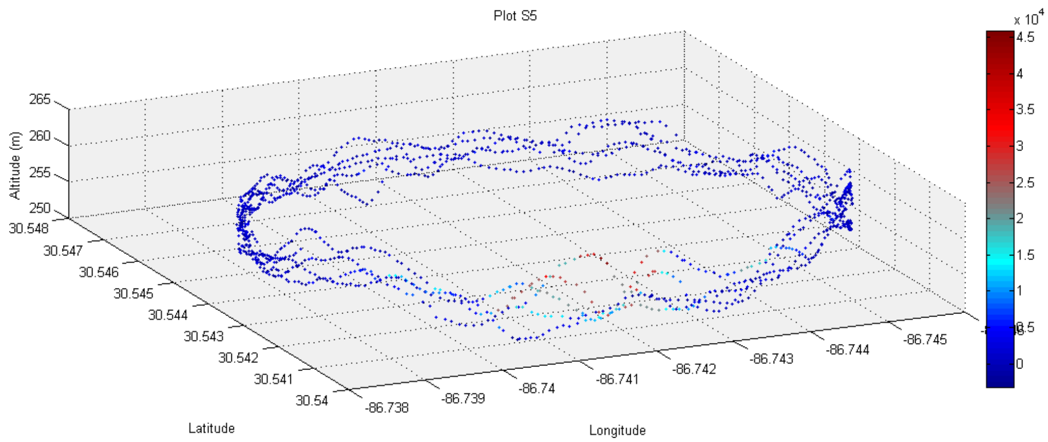


Fig. 11. Fire perimeter outlined and overlaying orthorectified LWIR image of small burn block S5 collected from the G2R. Burning charcoal pots (black dots on image) were used as infrared targets and their positions surveyed to aid orthorectification. See Dickinson *et al.* this issue, for more information.

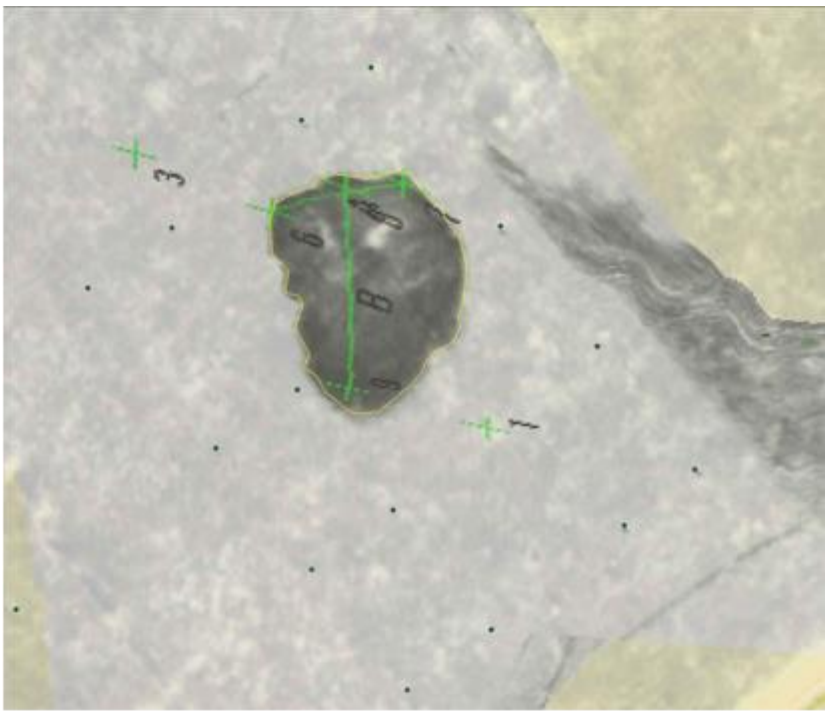
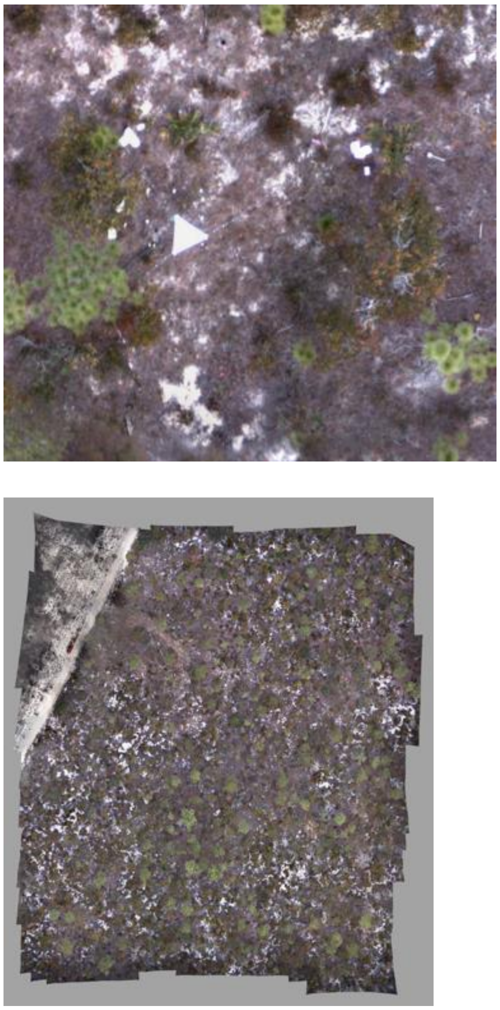


Fig. 12. (*a*) Nadir visible image (a cropped, single frame) from the Scout quadcopter (Note top of tripod visible near the center), and (*b*) image mosaic.



(a)

(b)