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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 provide important contributions to wildland fire operations and research, but their evaluation and use have been limited. Our objectives were to leverage US Air Force-controlled airspace to (1) deploy RPAS in support of the 2012 Prescribed Fire Combustion and Atmospheric Dynamics Research (RxCADRE) project campaign 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. Deployments of RPAS ranged both in time aloft and in size, from the Aeryon Scout quadcopter to the fixed-wing G2R and ScanEagle UAS. 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 long-wave infrared (LWIR) imagery, black carbon, air temperature, relative humidity and three-dimensional wind speed and direction.

Additional keywords: Aeryon Scout, black carbon, concept of operations (CONOPS), fixed-wing aircraft, G2R, remote sensing, rotor aircraft, ScanEagle, thermal imagery, three-dimensional wind, unmanned aircraft systems, vertical takeoff and landing.

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Introduction

In this paper, we describe remotely piloted aircraft systems (RPAS), also known as unmanned aircraft systems (UAS); 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 necessary improvements. The research described in this paper was secondary to evaluating the use of a new technology in a complex operational environment. It is included here to show the capabilities of RPAS technology and to illustrate why improvements are needed.

The use of piloted aircraft to collect infrared, visible and other passive imagery and active data such as light detection and ranging (LiDAR) has long been recognised 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 RPAS 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 behaviour of large prescribed fires for use in guiding ignition operations and on three-dimensional (3-D) wind fields upstream of fires. For wildfire operations, RPAS may provide imagery during night-time 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 2015), 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 programme 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; however, the research outcomes are not included from this campaign.

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 a rotor-wing piloted aircraft started them in order 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 that would be burned routinely as part of EAFB's fire management programme 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 organised 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 focussed 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 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 long-wave 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 20×20-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 focussed on three RPAS platforms—the Aeryon Laboratory'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^{TM} software package, a product of SRI International.

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 (100×200 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 focussed solely on finer-scale fuel conditions, micrometeorology and fire behaviour. EAFB 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 1–4-year rotation (see Ottmar *et al.* 2015). Range B-70 was chosen for the RxCADRE because the presence of non-forested 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 forward looking infrared (FLIR) camera (see O'Brien *et al.* 2015). In addition to these fixed towers, the US Environmental Protection Agency deployed a tethered aerosonde (tethersonde) 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 2015). They were chosen based on the operational RPAS and 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

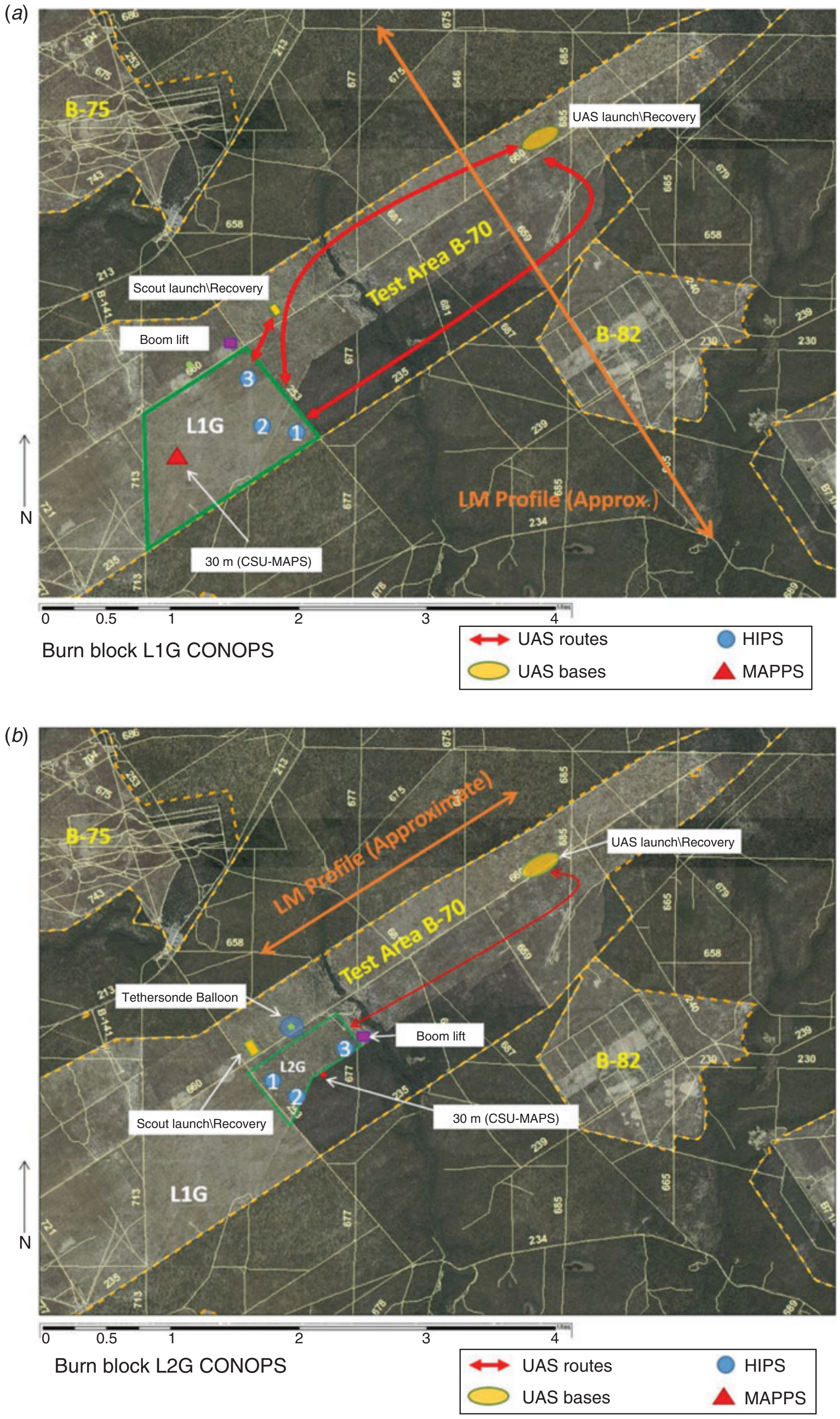

Fig. 1. Operational setting for large burn blocks. CSU–MAPS, California State University–Mobile Atmospheric Profiling System. Aircraft maintained a minimum of 155-m (unmanned) or 360-m (manned) buffer from the tethersonde balloon. (*a*) L1G, (*b*) L2G and (*c*) L2F.

(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 stabilised LWIR sensor. The ScanEagle was developed by Insitu, which is now a

(*c*)

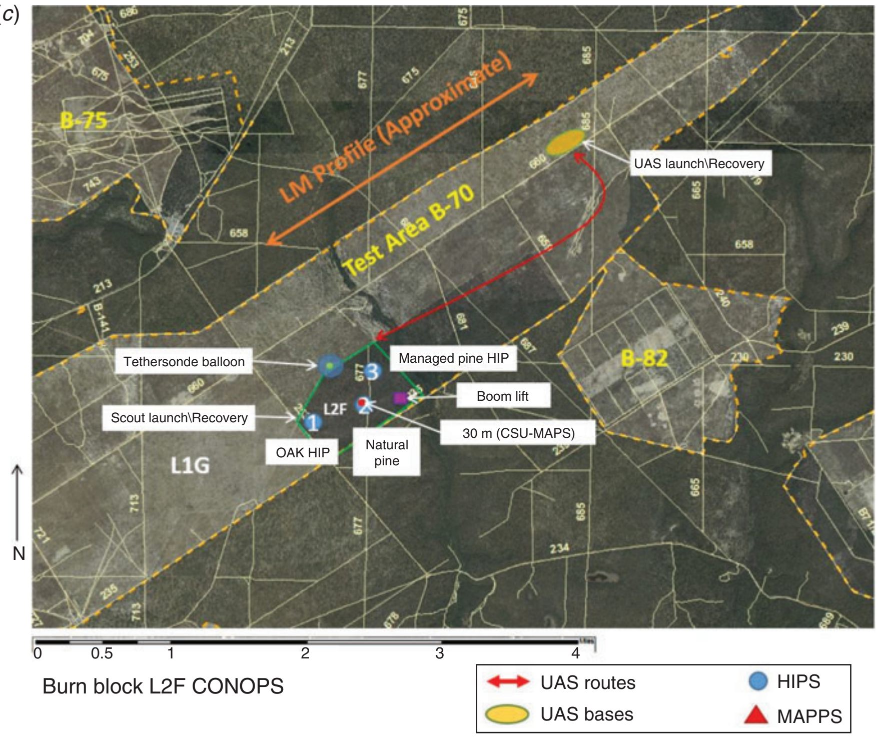

Fig. 1. (Continued)

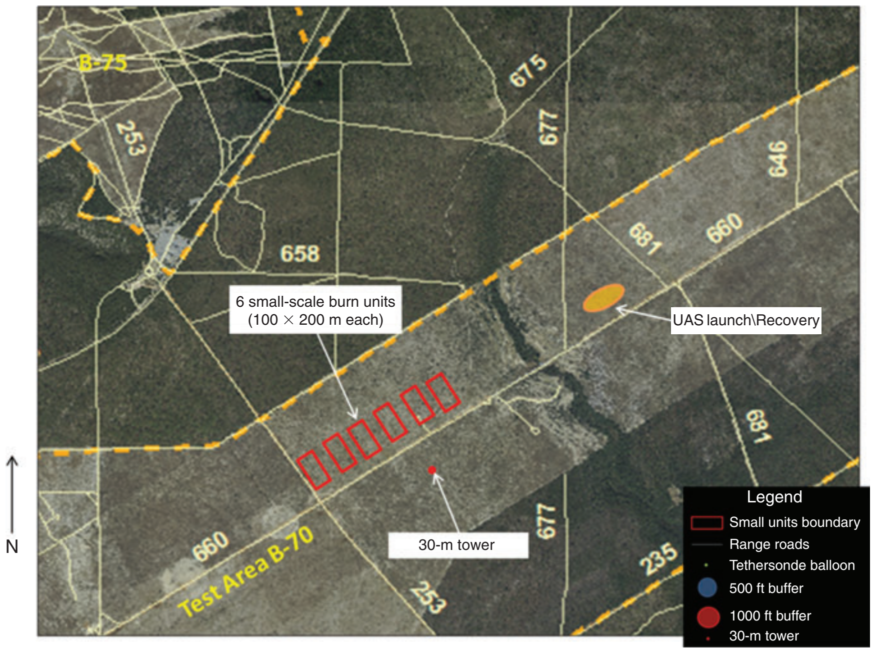

Fig. 2. Small burn block operational setting. UAS, unmanned aerial system.

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 that is engaged by the ScanEagle's wingtip hooks. The ScanEagle uses both an on-board 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

Table 1. Uplink and downlink frequencies for each of the remotely piloted aircraft systems (RPAs) supporting this demonstration

RPA 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

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 air temperature, relative humidity, wind speed and wind 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 EAFB. These simple and robust RPAS are well suited for remote operations through hand launching and belly landing. Table 2 gives 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 post-fire fuel samples (see Ottmar *et al.* 2015), fire radiation from nadir radiometers (see Hudak *et al.* 2015) and fire behaviour (see Butler *et al.* 2015). In addition, meteorological data and black carbon measurements were collected with on-board 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 post-fire natural colour 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, colour video and high-resolution still camera). 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 post-fire high-resolution images of the burn units from which mosaics were generated during fires; the Scout was flown as low as 15.24 m above ground level (AGL) to acquire 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 and the flight crew was escorted by the qualified fire line personnel.

Fig. 3. Remotely piloted aircraft systems 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.

Sensors deployed during RxCADRE 2012

The RPAS used several sensors based on the scientific requirements of their mission. Sensors included LWIR for flame front description and progression mapping; natural colour for characterising pre- and post-fire vegetation; meteorological for measuring air temperature, wind speed, wind direction (in three dimensions) and relative humidity; and particulate sensors for characterising smoke. Although the RPAS data have only been used in one study to date (Dickinson *et al.* 2015), in keeping the RxCADRE goals, RPAS data are archived for wide distribution and use in future studies (US Department of Agriculture Forest Service Research 2014).

Thermal infrared

The G2R and Scout were equipped with TAU 640s, which are a single-band, uncooled LWIR sensor made by FLIR. A 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 manoeuvring the aircraft vertically and laterally. The ScanEagle and Scout have their LWIR sensor mounted in a stabilised 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) whereas the sensor on the Scout had a nadir perspective.

Table 2. Specifications of the remotely piloted aircraft systems 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^{-1})	31	14	NA
Maximum speed (m s^{-1})	41	21	NA
Wind tolerance (sustained/maximum) (m s^{-1})			15/26

[A]From the tip of one rotor to the tip of the opposite rotor.

Infrared reference points were established at each plot to aid in orthorectification of LWIR imagery. The reference points were necessary because the LWIR sensors are subject to signal 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 IMU, manual control points and a digital elevation model of the earth to create accurate orthorectified images. Data from all RPAS, except the Scout, were orthorectified in real time at the command trailer and made available to the incident management team. TerraSight uses altitude 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 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. 3-D wind direction and speed were calculated using the RPAS GPS and IMU data. These sensors were flown over both the large and small burns.

Table 3. Infrared and visible camera specifications

NEdT, noise equivalent differential temperature (i.e. the minimum temperature difference a thermal camera can resolve)

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 (°)	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 (pixels)	380 000	1920 × 1080	
FoV (°)	57.8°(wide)–1.7°(tele)	50°(wide)–5.4 (tele)	50°(wide)–5 (tele)
Zoom optical	36 ×	12 ×	10 ×

Planning for RPAS operations

Incident organisation

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

CONOPS

The current FAA policy (FAA 2013*a*, 2013*b*) requires public (i.e. government) operators to obtain a Certificate of Authorisation 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 (US Government Publishing Office 1981). Integration of RPAS access, both public and commercial operations, into the NAS will require additional 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.

Although 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 ~5 km from the burn units. The staging area included the DVL Test and Analysis Capability (DTAC) support vehicle, which served as the coordination centre 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.

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

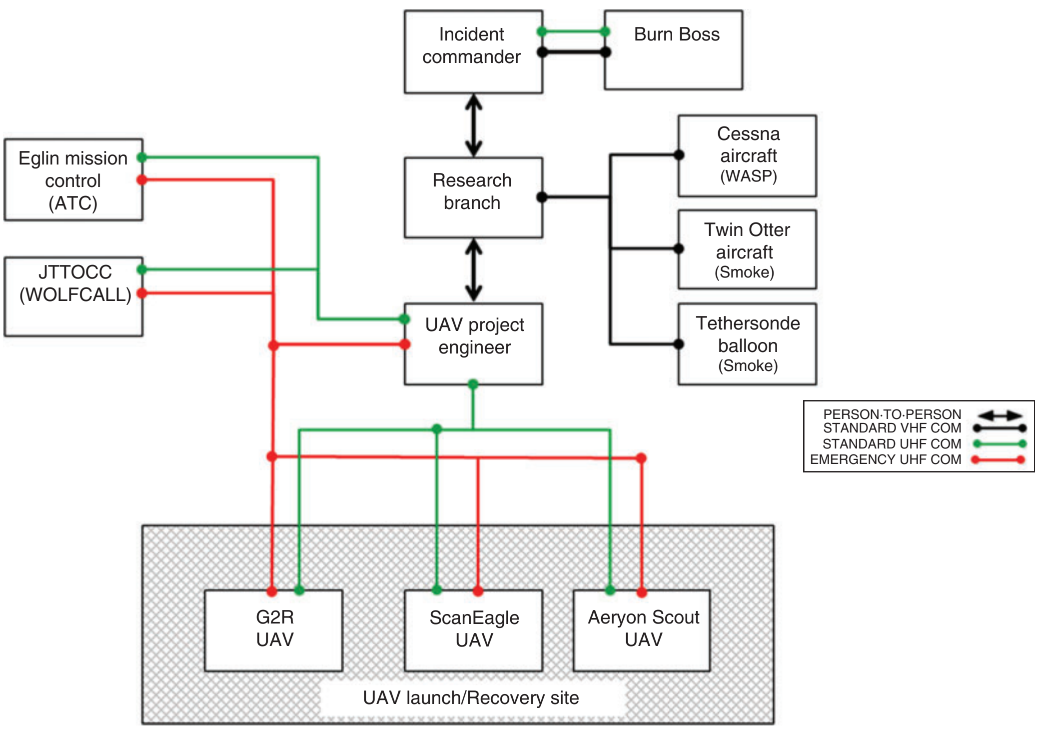

Fig. 4. Incident command communications structure. (ATC, Air Traffic Control; JTTOCC, Joint Test and Training Operations Control Center; UAV, unmanned aerial vehicle).

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 colour mosaics as well as detailed imagery around an 8.2-m tripod that elevated a nadir-viewing LWIR camera (see O'Brien *et al.* 2015). Due to battery limitations, two G2R RPAS were used so that the burn blocks would be imaged without gaps in overflight coverage until the burnout was complete. This LWIR imagery was used to quantify fire progression (see Dickinson *et al.* 2015). 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 altitude separation between platforms (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.

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

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

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

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 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 received an air operations plan that detailed the mission. Radio communication was maintained between the manned aircraft and the DTAC, which

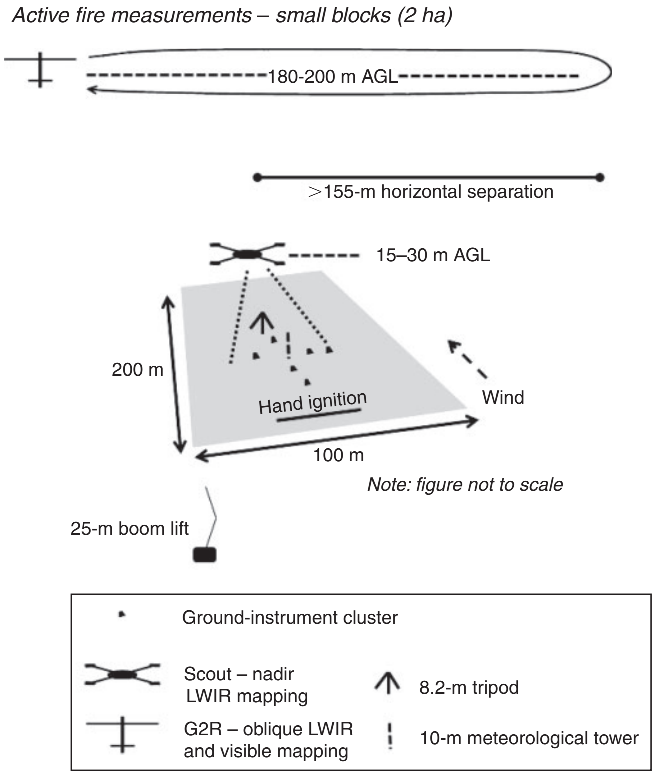

Fig. 5. Small burn block general flight coordination. LWIR, long-wave infrared; AGL, above ground level.

was in contact with the Incident Commander (Fig. 4). In addition to position reports given by the pilots, the Research Branch Chief was able to monitor the near-real-time position of the manned aircraft and RPAS through the Sarnoff TerraSight 3-D Visualiser at the DTAC.

The DTAC 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 3-D Visualiser or similar COP will give incident command teams the situational awareness needed to implement safe RPAS operations when used in conjunction with standard aviation CONOPS.

The overarching consideration in 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 (Dickinson *et al.* 2015; Hudak *et al.* 2015) and a Cessna 337, low (altitude) manned (LM), equipped with smoke sampling equipment (Strand *et al.* 2015). 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 similar 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 manoeuvre was complete, the LM would fly downwind 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.

Although 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

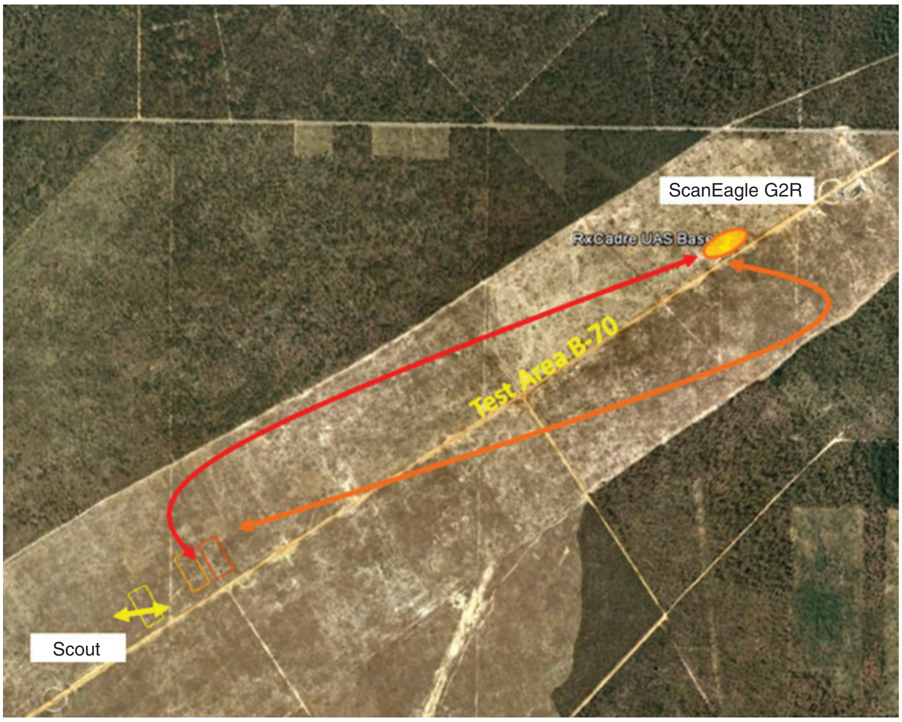

Fig. 6. Flight paths used to maintain separation among the three remotely piloted aircraft systems deployed during small block burns.

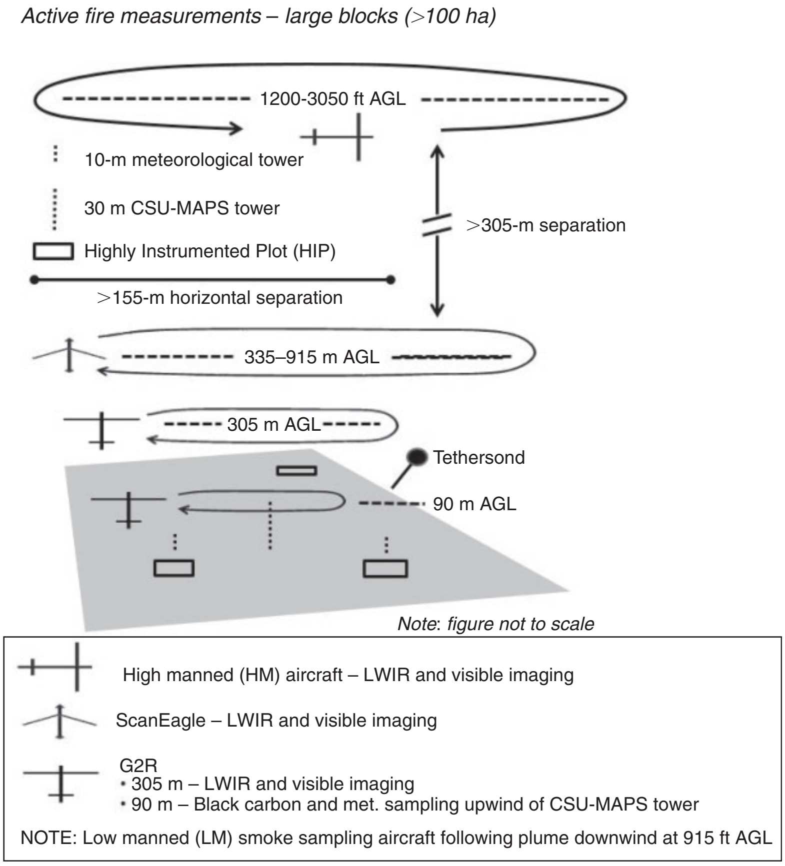

Fig. 7. Large burn block general flight coordination. AGL, above ground level; CSU–MAPS, California State University–Mobile Atmospheric Profiling System; LWIR, long-wave infrared.

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 that was orthorectified by an 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. 3-D 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 found 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 h 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 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.* 2015), 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 behaviour. A recent demonstration of 'fused' LWIR (Tau 640) and visible (colour) 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 it 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 necessary for sensors and image analysis appropriate for wildland fire operations, which will require dedicated laboratory and field testing. Regardless, operation objectives were far exceeded by the RxCADRE incident. The situational awareness provided by

Table 6. Operations schedule for example large burn block L1G

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

Time (local)	Event
1100 hours	Launch weather balloon 1
1115 hours	LM takeoff
1115 hours	Launch ScanEagle
1130 hours	LM begins sampling over burn block once ScanEagle is upwind of block
1130 hours	HM takeoff
1145 hours	Launch G2R1
1155 hours	Launch G2R2
1200 hours	Ignition and launch Scout
	• LM cleared to fly downwind as desired
	• HM makes passes 1200 m above ground level (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 hours	Retrieve G2R1 once LM confirms it is clear of Range B-70 (treeline) or is above 1800 m AGL
1215 hours	Retrieve Scout
1220 hours	LM cleared to profile as desired downwind of block
1230 hours	Re-launch Scout (as needed/directed)
1230 hours	Re-launch G2R1 once LM confirms it is clear of Range B-70 (tree line) or above 1800 m AGL
1230 hours	Retrieve G2R2
1240 hours	LM cleared to profile as desired downwind of block
1245 hours	G2R1 on-station, orbiting 180 m AGL over California State University–Mobile Atmospheric Profiling System tower
1330 hours	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 hours	Launch weather balloon 2
	• Confirm LM is well clear downwind
	• Confirm HM has departed Range B-70
	• Confirm ScanEagle has landed

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.* (2015). 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 (US Department of Agriculture Forest Service Research 2014).

Example data products

The ScanEagle orbited the large burn blocks at ~465 m AGL, obtaining oblique LWIR imagery at the same time as the piloted aircraft was collecting nadir LWIR imagery from passes every ~3 min from an altitude of >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 behaviour model evaluation (R. Linn, pers. comm.).

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 whereas the second was flown to obtain smoke particulate concentrations, 3-D 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' on-board 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.* 2015). An example orthorectified false-colour LWIR image from the G2R of a small burn block is shown in Fig. 11.

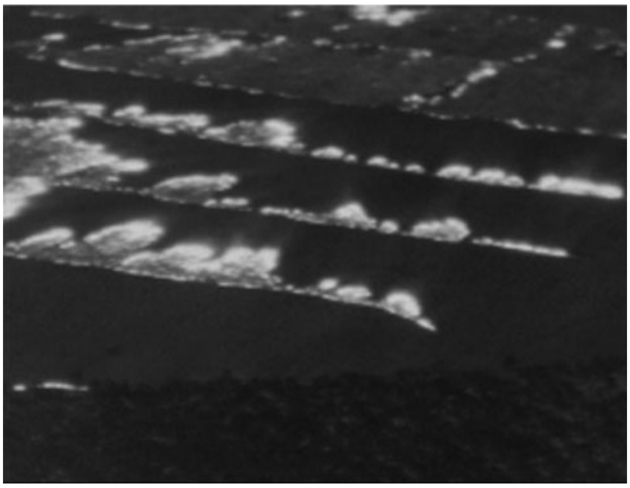

Fig. 8. ScanEagle oblique long-wave infrared imagery of block L2G from a south-easterly perspective.

Fig. 9. Oblique long-wave infrared (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.* 2015) and dual-band radiometer (Dickinson *et al.* 2015). This image is from large block L2F.

In addition to the focussed monitoring of fire spread in a HIP, the Scout was flown opportunistically both before and during burns in large and small blocks (Fig. 12). The team discussed flying the Scout above the centre of the small units at an altitude sufficient to image entire 100 × 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 ground instrumentation 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.* 2015). Because of the need to maintain perspective, it was not possible to obtain useable images at a smaller time interval than 1–2 min. 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 factors 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 programme 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). 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. It is clear that better RPAS 3-D positional data are needed given weight and cost limitations of the platforms and sensors. Several companies and universities are working on this issue. Nonetheless, a certain amount of error, larger than that 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, and secure, reliable command and control, and data linking 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.

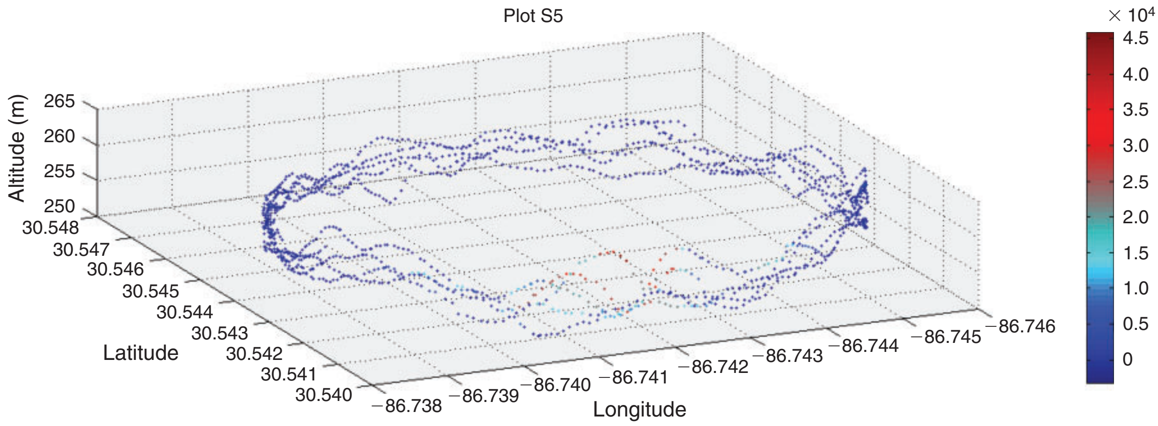

Fig. 10. Relative concentrations of black carbon particles over the S5 burn block. Data were collected from a G2R flown in a racetrack pattern upwind of a 30-m meteorological tower. (For colour key, see online version available at http://www.publish.csiro.au/nid/17.htm.)

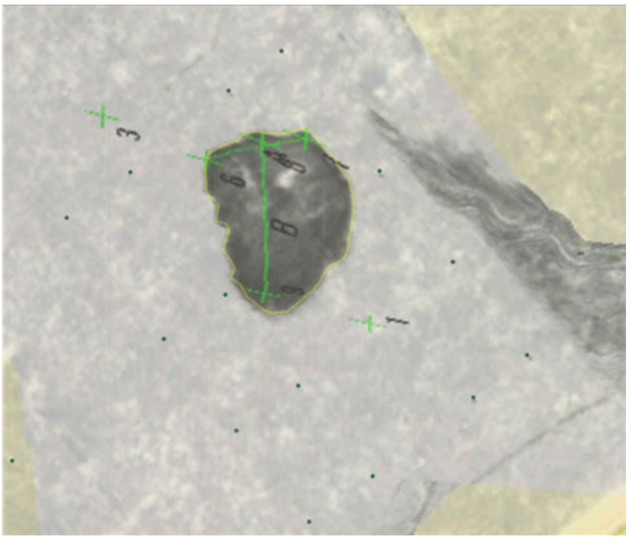

Fig. 11. Fire perimeter outlined and overlaying orthorectified long-wave infrared image of small burn block S5 collected from the G2R. Burning charcoal pots (black dots on image) were used as infrared targets and their positions surveyed to aid orthorectification. For more information, see Dickinson *et al.* (2015).

As data from RxCADRE 2012 RPAS are used for research studies (e.g. Dickinson *et al.* 2015), 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 miniaturised infrared sensors deployable on small RPAS that provide more quantitative data is critical. Also, 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 behaviour measurement, event-scale fire mapping, and emissions and event-scale plume behaviour. 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.

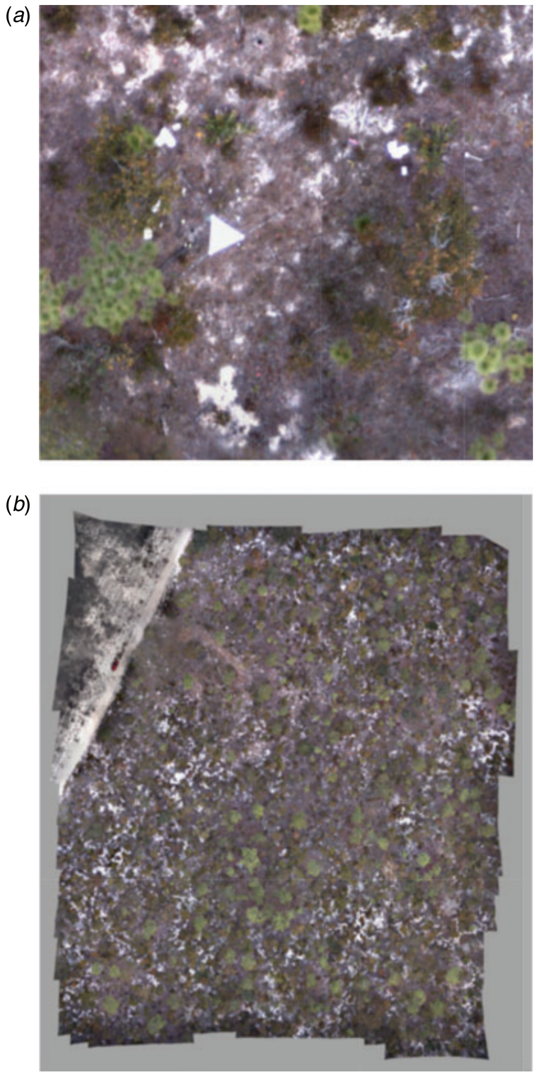

Fig. 12. (*a*) A nadir visible image (a cropped, single frame) from the Scout quadcopter (note top of tripod visible near the centre) and (*b*) image mosaic.

On 24 February 2015 the FAA released the long-awaited Notice of Proposed Rulemaking for small unmanned aircraft (FAA 2015). After undergoing a public comment period the FAA is expected to finalise the rule sometime in 2017. The proposed rules would allow operation of all of the RxCADRE 2012 RPAS as well as similar LASE RPAS during daylight hours, 150 m or less above the ground, within line of sight of a certified operator. This new rule will allow for many of the operations we have described in this paper, except for the synaptic overview, which will still require a Certificate of Authorization (COA) because that mission requires the RPAS to remain at higher altitudes. Hopefully the rule will allow routine operations for operational fire managers and researchers.

The RxCADRE 2012 campaign was very complex with multiple RPAS and manned aircraft operating in the same area. This was possible due to the experience of the 96th TSSQ in developing robust CONOPS. Presently the Department of the Interior and the United States Forest Service are working on how to integrate RPAS into their operations. This will begin with small RPAS operating on a prescribed burn before moving on to manned or unmanned teaming, or night operations.

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.

In memoriam

It is with profound gratitude that we remember the loss of two RxCADRE colleagues, Dr Otto Martinez and Mr Bill Holley, who played such critical roles in advancing the science and application of RPAS on this project. Since the first discussions of the RxCADRE project, the Eglin AFB Digital Video Laboratory led by Otto and Bill was actively engaged in planning and deploying RPAS technologies in the wildland fire environment. Their collective expertise was in acquiring, synthesising and displaying data streams in real time from both manned and unmanned platforms, but they expertly led the team through numerous safety briefings and planning milestones that allowed us to deploy multiple RPAS and co-altitudinal manned flights in very complex military airspace. Otto was a creative genius and played Bill the ever-practical straight man, but both loved the excitement of applying technologies to wildland fire that would one day not only advance fire science but also firefighter safety. We miss their laughter and enthusiasm.

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