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Use of night vision goggles for aerial forest fire detection

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Abstract. Night-time flight searches using night vision goggles have the potential to improve early aerial detection of forest fires, which could in turn improve suppression effectiveness and reduce costs. Two sets of flight trials explored this potential in an operational context. With a clear line of sight, fires could be seen from many kilometres away (on average 3584 m for controlled point sources and 6678 m for real fires). Observers needed to be nearer to identify a light as a potential source worthy of further investigation. The average discrimination distance, at which a source could be confidently determined to be a fire or other bright light source, was 1193 m (95% CI: 944 to 1442 m). The hit rate was 68% over the course of the controlled experiment, higher than expectations based on the use of small fire sources and novice observers. The hit rate showed improvement over time, likely because of observers becoming familiar with the task and terrain. Night vision goggles enable sensitive detection of small fires, including those that were very difficult to detect during daytime patrols. The results demonstrate that small fires can be detected and reliably discriminated at night using night vision goggles at distances comparable to those recorded for daytime aerial detection patrols.

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Introduction

Night vision goggles (NVGs) are head-mounted electro-optical devices that amplify available light in a scene, greatly improving visibility. When used for night-time aerial detection patrols, NVGs have the potential to improve response times to nascent fires and to improve sensitivity. In Ontario, approximately half of all wildland fires are ignited by lightning strikes (Wotton and Martell 2005). An extensive lightning sensor system combined with modern predictive modelling can indicate areas with a high probability of new starts. We envisaged that it would be advantageous to fly night-time detection patrols following thunderstorm activity to detect fires early and permit suppression with minimal delay. Jennings *et al.* (2007) described preliminary investigations of the utility of NVG-aided forest fire suppression operations, concluding that NVGs 'have potential to improve the safety and efficiency of airborne forest fire suppression, including forest fire perimeter mapping and take-off and landing in the vicinity of open fires. [Night vision device] operations at some distance from the fire pose minimal risk to flight, and provide an enhanced capability to identify areas of combustion at greater distances and accuracy.'

The success of airborne sensing inevitably depends on looking in the right locations. The Ontario Ministry of Natural Resources' (OMNR) approach to aerial detection of fires is outlined by McFayden *et al.* (2008) and is guided by real-time weather, smoke, fuel and other data interpreted by experienced analysts, historical trends and state-of-the-art models. In terms of fire prediction and planning in Ontario, the model of Wotton and Martell (2005) is used to predict the incidence of lightning strike ignited wildfires based on fuel moisture levels, rainfall, lightning strike location and other parameters. Ideally, such prediction tools would direct the aerial detection patrol to an area where fire occurrence is likely and efficient detection can occur. As well as facilitating safe night-time detection patrols, NVGs can be directly beneficial in detection, as the visibility of fires at night with NVGs is high. Fig. 1 shows unaided and NVG-aided pictures of an active fire at night. Note that, because the human eye has a very large dynamic range compared to the camera, the outlines of the forest canopy and the shoreline, and so on, were more visible for both naked-eye and NVG-aided viewing than in the camera images presented. Even so, little evidence of the fire could be seen by the naked eye.

NVGs differ from thermal infrared (IR) cameras – which can also be used for night vision – in that NVGs rely on high-resolution image intensifier tubes to amplify visible and near infrared light reflected from the scene (e.g. wavelengths in the

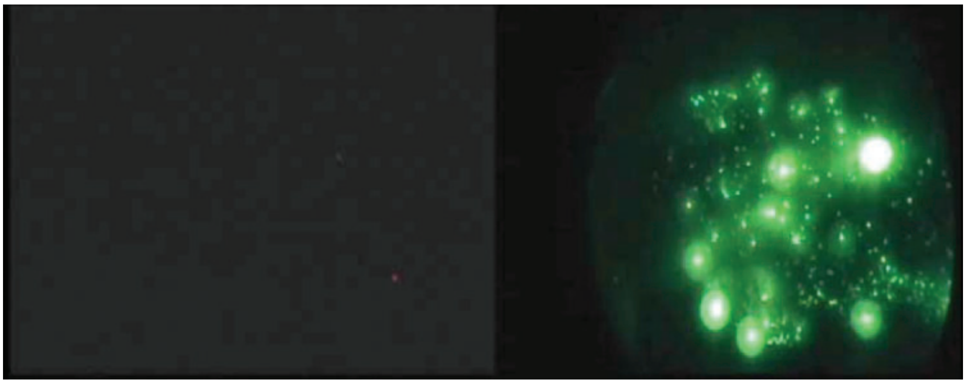

Fig. 1. Left-hand side shows 'naked eye' image of an active wildfire; right-hand side shows a simultaneously acquired NVG image of the same fire from the same viewpoint.

625–900-nm range for typical aviation NVGs), whereas thermal IR cameras can detect thermal emissions (longer wavelength IR) but usually with lower resolution. Typically, both thermal IR cameras and NVG devices have restricted field of view (extent of the scene that can be imaged at any instant) due in part to the requirement to maintain adequate resolution with a limited number of sensor elements. This limited field of view requires the user to scan the device in order to inspect or search an extended scene. As hand-held IR cameras are difficult to stabilise and cannot see through glass they are usually mounted outside the aircraft cockpit, scanned remotely with gimballed motors and viewed on a cockpit display. Compared with typical IR scanning operations, NVG detection at night is more like ocular detection scans in daylight. Specifically, the observer's natural search abilities and spatial abilities are optimised by the 'egocentric' nature of the helmet-mounted device, which moves naturally with the observer's gaze. This potentially allows for many of the benefits of IR detection to combine with the efficiency and coverage of ocular detection. Further, NVGs permit hands-free scanning for fires by all members of the crew including the pilot (piloting tasks permitting), which could increase the probability of detecting a fire.

Despite this potential and some success in operational use, there are few published studies on the effectiveness of NVGs in wildfire suppression activities. The flight trials described in this report were designed to explore the potential for NVG-aided detection in (1) an operational context with experimental control and 'ground truth' knowledge of the fire source, and (2) aerial detection patrols in support of normal fire detection and suppression activities. Specifically, to assess the feasibility of detecting wildland fires at night, we explored whether (a) small fires could be detected at night and (b) wildland fires could be discriminated from other light sources.

Experiment 1: detection of point source fires under controlled conditions

Methods

A series of flight trials were run from the evening of 22 April to the morning of 26 April 2010 over a test grid in the vicinity of the city of Pembroke in the Ottawa Valley region of Eastern Ontario, Canada. This experiment sought (1) to examine the efficacy of NVGs in the aerial detection of forest fires in a controlled setting (2) to determine suitable flight parameters (altitude and flight path) for NVG detection patrols, and (3) to determine the feasibility of detecting and discriminating wildland fires from other light sources under varying canopy in the region.

Flights and observers

For each flight, detection and classification of fires was performed by a single observer. Over the course of 3 nights of detection testing, 12 observation sorties were flown (five, five and two sorties respectively on the evening–morning of 23–24, 24–25 and 25–26 April). Six observers participated in two detection sorties across different nights with different target fire configuration and locations, for a total of 12 sorties. An additional three sorties were flown on 22–23 April to determine suitable ground speed and altitudes for effective detection over the terrain. All observers were trained in fire detection techniques but had no previous experience in fire spotting. Training consisted of the standard fire detection observer training course run by the OMNR, simulations of fire detection scenarios, and instruction on the set-up and use of night vision goggles.

The flight crew consisted of five or six people: two pilots, an audio–video technician, an experimenter and the observer (on some flights an additional experimenter tested a tablet-based fire logging system but this did not interfere with the main experiment). The pilots were the only members of the flight crew aware of the test grid location. However, they were not aware of fire locations and profiles, and did not provide any information to the observer. The observers alone were responsible for detecting fires and recording them. No other crew member was allowed to assist the observer during a detection flight. The experimenter kept a paper log as a backup and marked detection, discrimination and confirmation waypoints and the time of detection. The audio–video technician continually recorded audio and video during flights.

Observers filled out a brief questionnaire to indicate the number of hours they had slept and their current level of fatigue. Sorties typically began at 2130 hours each night and continued until ~0200 hours.

After each flight the observer was required to fill out a debriefing questionnaire covering the ability to cover the search area, search strategy, visual performance, spatial orientation, NVG side effects, situational awareness and other factors (see Supplementary material for details and results pertaining to the debriefing questionnaire).

Apparatus

All flights took place in an EC130 helicopter (Airbus Helicopters, Marignane, France). A hand-held Garmin GPS 96C (Garmin International, Inc., Olathe, KS, US) was used to mark the aircraft location in real time. This unit reported aircraft position every 15 s. The specified accuracy of the Wide Area Augmentation System was less than 3 m, 95% of the time. In addition, automated flight-following data from the aircraft were also obtained. This system reported the aircraft's position every 60 s over a radio link.

Generation III ANVIS 4949 binocular NVGs (ANVIS 4949 binocular NVGs, ITT Corp., Roanoke, VA, USA) were used. A Canon FS200 recorded video (Canon Corp., Tokyo, Japan). Audio from the cockpit was fed directly into the camera.

Plot profiles

The test grid consisted of 109 surveyed locations for precisely located test fires. Based on the universal transverse mercator (UTM) coordinate system, the grid was 100 ha with each plot point spaced on 100 × 100-m grid intervals. Canopy density and type of tree coverage varied with each plot and included dense coniferous, dense or semi-dense mixed, and dense or semi-dense deciduous stands. Although it was still springtime, the canopy for the deciduous stands was beginning to fill in, likely due to the mild weather. Elevation of the plots varied between 215 and 295 m above mean sea level (ASL).

Target fires

On each of the four nights, one to six small test fires were lit at locations within the grid. A total of six simulated fires were lit on 22–23 April (i.e. starting on the night of 22 April and continuing into the morning of 23 April), four fires on each of 23–24 and 24–25 April, and one fire on 25–26 April. Fuels for the test fires were placed in aluminium 30 × 40-cm, fire-proof containers. In many instances, multiple sources were combined in a single plot to simulate a larger fire. Fuel sources were charcoal briquettes (Royal Oak brand briquettes, Royal Oak Enterprises, Roswell, GA, USA, 6.3 × 6.3 × 3.8 cm; ~60 briquettes lit with starter fluid), artificial fireplace logs (Ecolog Citronella Logs, Canadian Tire, Toronto, Canada, 30 × 10 × 10 cm, 0.9 kg) and alcohol gel torches (385-mL can).

Fires were monitored visually and through temperature readings made with thermocouples and a data logger. Log fires tended to rise rapidly in temperature shortly after being lit, then gradually decline in temperature throughout the evening; they tended to smoulder much longer than other fires, lasting into the late morning. Charcoal briquette fires typically burned hottest after lighting, presumably due to the open flame and effects of the starter, before entering a phase of approximately exponential decay in temperature. The temperature of torch fires typically increased rapidly then burned uniformly (with spiking and oscillatory fluctuations likely due to wind gusts and variations) before decreasing rapidly. As a result, the torch fires were a well-controlled target until they began to extinguish. The rapid extinction essentially makes these sources both present and stable (on the scale of minutes although flickering on a shorter time scale), or essentially 'out'. However, they were very small and gave off little light, making them the most difficult target to spot.

Ground crews monitored the fires throughout the night; in some instances refuelling was required.

Detection procedure

On each night, a detection route was planned that brought the aircraft near the test grid. In flight, the observer scanned their visible area for potential fires. The observers were the only members of the flight crew responsible for detecting fires. Observers were always seated in the front right seat of the aircraft. This means they were unable to see the areas behind and to the rear-left of their position.

Once the observer spotted a target of interest they notified the pilots and experimenter. The experimenter provided the observer with a waypoint and time, which marked the aircraft's location for target detection. The pilots then deviated from the flight path towards the target. Upon closer inspection the observer either confirmed or rejected the target as a fire. Once again, a waypoint and time was recorded to mark the aircraft location for target discrimination. If the target was confirmed as a fire, its characteristics, such as intensity, size and fuel source were recorded. A final waypoint and time was recorded as the aircraft passed or hovered over the fire to mark the approximate fire location. Once all the required data were recorded the aircraft returned to the original planned flight path. If a target was identified as a bright light but not a fire, the observer attempted to categorise the target.

Conditions

During data collection there was a first quarter moon, which provided ample ambient light for NVG use. All observers reported NVG visibility as good and atmospheric conditions were favourable. Unless otherwise stated, calm winds and clear skies prevailed with a visibility of 14 km (9 miles) and wind speeds between 0 and 19 km h^{-1} (0 and 10 knots), gusting to 39 km h^{-1} (21 knots) on one night.

Results

Speed and altitude

Three sorties on the first night were used to determine suitable altitude, flight patterns and patrol distances for subsequent nights. Observers on these flights reported that a height of 1219 m (4000 feet) above ground level (AGL) enabled a greater detection range because of the increased scanning distance compared to 762 m (2500 feet) or 305 m (1000 feet) AGL. A ground speed of ~167 km h^{-1} (90 knots) was deemed suitable for detection with adequate coverage of the search area. Thus, a target altitude of ~1219 m (4000 feet) AGL and speed of 90 knots was selected for the search phase of flights. Lower altitudes and occasionally lower speeds of 111 km h^{-1} (60 knots) were necessary when attempting to discriminate fire characteristics. Suitable choices for search airspeed and altitude will depend on terrain and canopy conditions.

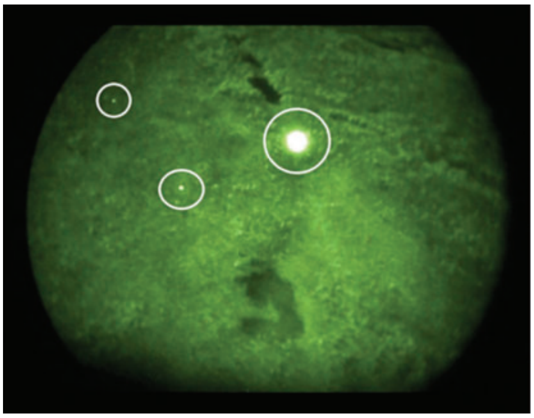

Fig. 2. NVG image from the patrols on 23–24 April 2010. The image shows of one of the brightest fires (far right) at Plot 57, the fire at Plot 103 (bottom) and the faintest fire at Plot 99 (top left corner). The second brightest fire at Plot 46 is not visible in this image.

Detection performance

On the first night of detection trials (23–24 April), fires on four plots were lit. On all four plots, 'fires' consisted of multiple sources separated to simulate a larger fire. The first plot contained three fire containers separated by 4.6 m, each fuelled by two artificial fireplace logs. The simulated fire on the second plot consisted of two briquette fires placed 3.0 m apart. The third fire plot contained three torches configured 4.6 m apart. During the final sortie of the night the torches went out. As a result, that observer had only three targets to identify instead of four. The fourth plot contained a mixture of fuel sources: one charcoal briquette, one log fire that consisted of three logs, and one torch fire.

Two of the fires, both containing fire log sources, were simultaneously the first fires to be detected by four of the five observers. One of these four spotted the brightest two fires and confirmed them as such; however, after closer inspection that observer retracted their previous confirmation. These were recorded as misses. Video footage confirms that these two fires were the largest and brightest of the targets (Fig. 2). Two observers failed to detect the other dimmer fires. A review of the video footage showed that the fires were faint, but still visible from the air. One campfire was detected and confirmed on one of the flights.

On the second night of detection trials (24–25 April) there were four fire arrangements in total and five sorties with five different observers. One observer did not detect any fires after deviating from the planned path to investigate an environmental light source. Also, the observer during the last sortie found no planned fires because all of them were extinguished by that time (confirmed by data logger readings). However, this observer found two campfires elsewhere on the patrol. The other three observers found all of the fires. There was one bright fire arrangement, consisting of three fire-log sources, which seemed to draw observers close. Once they were circling the area to record fire characteristics they were able to detect the three surrounding dimmer fires (which were all torch fires: two simulated fires consisted of a single torch and one simulated fire contained two torches). During the second flight the observer detected an unknown light source and confirmed it (erroneously) as a fire; this event was therefore classed as a false alarm. From review of the video footage, it is believed to have been a lantern or flashlight.

Table 1. Signal detection rates across all nights and on each night
n, number of observers; FA, false alarm; CR, correct rejection

Night	*n*	Hits	Misses	FA	CR	Hit rate (%)
23–24 April	5	9	10	0	12	50
24–25 April	4	12	4	1	13[A]	75
25–26 April	2	2	0	0	5	100
Overall	11	23	14	1	17	68 (62% pooled)

[A] $n = 5$ for correct rejections but not hits as all targets were extinguished for one observer's flight; campfires not included.

On the final night, there was one large fire arrangement, which consisted of a central briquette fire and six smaller torch fires. They were configured so that there were three torch fires on either side of the central briquette fire. Both observers who flew that night were able to detect this fire.

Detection distances

Isolated light sources could be seen at distances of many kilometres (detection) but observers needed to be nearer to identify a light as a potential source worthy of further investigation (discrimination). The average detection distance across all nights was 3584 m (95% CI: 2697–4471 m). Of all the detection events 44% were actual fires. The average discrimination distance, where a source could be confidently determined to be a fire or distracter, was 1193 m (95% CI: 944–1442 m). There was no significant correlation between distance and discrimination distances.

Signal detection

Table 1 illustrates the number of hits, correct rejections, misses and false alarms on each night and across all nights. The categories were defined in terms of the fire report generated:

- *Correct rejections* were defined as any target that was pursued and correctly identified as a bright light but not a fire.
- *Misses* occurred when a fire was not detected, or was detected but not confirmed.
- *Hits* occurred when a fire was correctly identified and confirmed.
- *False alarms* occurred when a distractor (bright light) was erroneously confirmed as a fire.

The hit rate for each night was calculated by averaging the observer hit rates (number of fires the observer found divided by number of actual fires). For the overall hit rate across the experiment (last row in Table 1) we made two calculations because the number of targets varied over the nights of the experiment. We calculated the average of the hit rates obtained on each flight as well as the 'pooled' hit rate based on the numbers of hits and misses tallied across all the flights. The mean hit rate across the flights was 68% and the pooled hit rate was 62%. Note that there were five observers on 24–25 April, but only four were counted in hit rates because the planned fires were extinguished during the last sortie. All five observers were counted for correct rejections during that night.

The hit rate (Table 1) shows that observers improved over time: there was a 50% hit rate on the first evening and a 100% hit rate by the last evening (although only two observers flew). Observers had participated in two sorties and experience seemed to improve performance although brightness and fire size probably contributed to these improvements as well.

Correct rejections were broken down according to the type of distraction (see Table S1 in the Supplementary material). Man-made structures (mostly houses) provided the largest challenge for observers because they made up the majority (70%) of distractions. Vehicles accounted for 23% of distractors and 7% of distractors could not be identified. Of all the events spotted across three nights 44% were actual fires, whereas the other 56% were distractions. For these calculations any event that was not a fire was collapsed into one category. Across all nights there were 59 events in total. Of these 59 events, 26 were fires (three of which were campfires). The other 33 were a mixture of correct rejections and false alarms. It is clear that distinguishing fires from other light sources is a major component of the detection task.

Discussion

The sources used were very small by typical aerial detection patrol standards: they were essentially point sources. Fire managers would not normally expect daytime patrols to find fires this small. Nevertheless, the average hit rate (68%) was higher than expected based on the use of small fire sources and novice observers. The hit rate showed improvement over time, likely because of observers becoming familiar with the task and terrain. One novice observer detected two actual fires on their first detection patrol but could not confirm them as actual fires; another observer missed targets because of a change in flight path to investigate an environmental light source. Correct rejections were common (30 events out of 59), likely because of the large number of environmental lights in the test area and the inexperience of observers. Flickering lights from vehicles and houses behind the canopy were most likely to be detected and subsequently correctly discriminated from fires. Correct rejections declined with time, perhaps as observers became more discriminating in which targets they chose to investigate. There was only a single false alarm, when one observer falsely identified a non-fire target as a fire. Thus, it is apparent that small fires can be detected and reliably discriminated from typical detection patrol altitudes and distances. The next phase investigated NVG-aided detection in an operational context.

Experiment 2: NVG-aided detection during aerial detection patrols

A total of 14 detection flights took place across eight nights between May and August 2010 in the vicinity of Sudbury, Ontario. The objective was to explore the utility of NVG-aided detection in the real operational context. The aircraft and experimenters were based out of the local airport and flew an average of two detection patrols per night. All crew members were responsible for detecting and discriminating fires.

Methods

Materials and methods were generally similar to the controlled experiment with modifications for operational flights as described below.

Detection patrols

The OMNR continually monitored real-time weather information, forest fuel indices, historical trends and other indices. The flight trials were conducted when the weather and fuel indices were conducive to lightning strike fires. Each night the Aircraft Management Officer planned two detection routes that brought the aircraft over an area that had recently been subject to a large number of lightning strikes. Detection patrols typically flew at an altitude between 914 m (3000 feet) and 1219 m (4000 feet) AGL and at a speed between 111 $\mathrm{km\,h^{-1}}$ (60 knots) and 167 $\mathrm{km\,h^{-1}}$ (90 knots).

Flights typically began at 2230 hours each night and continued until ~0400 hours the following morning. Across groups of flights the moon phase varied from full to no moon. Total flight time was ~28 h. A summary of the conditions for the flights is provided in Table S2 in the Supplementary material.

Materials

Materials and apparatus were as previously described for the controlled experiment with the following exceptions: (1) detection activities involved real fires so the controlled sources and dataloggers were not required, (2) most flights took place in an EC130 helicopter, although during one sortie it was necessary to fly in an AS350, and (3) IR still images were taken using a FLIR ThermaCAM P25 (FLIR Systems, Inc., Wilsonville, OR, USA).

All crew wore Generation III, ANVIS 4949 binocular NVGs.

Flight crew roles

Flight crew complement and roles were similar to the controlled experiment described above; however, all crew members were responsible for detecting fires. The pilots had NVG certification and extensive detection experience. Occasionally it was necessary to fly without an audio–video technician and during three flights there was one pilot instead of two.

In flight, the scanning, detection, discrimination and classification of fires followed the same procedure as the controlled fire trials; however, all crew members now contributed to these tasks and conferred on the decisions. As in the earlier study, GPS waypoint and time were used to mark the aircraft location for target detection, target discrimination as a fire or not and approximate fire location.

Determining ground truth

Unlike the controlled experiment where target fires were known, observers on these flights were looking for real fires in an uncontrolled environment. We were principally interested in (a) hits or the number of fires present along the route that were actually detected, (b) misses or actual fires along the route that were not found and (c) false alarms or reports of fires that did not correspond to actual fires. The difficulty in assessing these numbers is in knowing the ‘ground truth’. To estimate hits and false alarms, all fires reported were followed up either by matching to the database of current fires or by visual verification on the ground. Misses were estimated from analysis of fire reports and status for the day of the flight and subsequent days as logged in the OMNR's database. This is likely to overestimate miss rates as fires take time to develop and conversely are sometimes essentially extinguished before being officially declared out. Miss rates were calculated given assumed visibility relative to the flight path with separate estimates of the rates for the reported visibility on the relevant night, a range of ±10 km and a range of ±20 km. The true number of fires in a given range was determined by measuring the distance of active (at the time of the flight) fires from the flight path and tallying fires within the specified visibility range. The hit and miss rates were calculated by dividing the number of forest fires spotted or missed by the total number of forest fires within the range of visibility.

It is important to note that the crew were not informed of the existence or location of existing fires and thus detected fires were truly (new) hits for the detection patrol. Similarly, if known active fires within range of the aircraft were not detected, they were recorded as a miss.

Results

As an example, Fig. S1 in the Supplementary material shows a flight path from the first night of flights (27 May) with all active fires in the vicinity marked. Three fires were found during this flight, two of which were previously unreported. The fires were confirmed by day patrols, ranged from 0.1 to 0.8 ha in size and were of modest intensity (Canadian Forest Fire Behaviour Prediction System, Rank 2; Taylor *et al.* 1996). The North Bay 29 (NOR29) fire was estimated at 0.4 ha in size by the night-time detection crew, but was later confirmed to be 0.8 ha. Distance and size estimates using NVGs can be problematic (discussed below), which may explain why NOR29's size was underestimated. Two fires were missed during this evening. At a visibility of 10–15 km the night patrol missed one fire, NOR27. At a visibility of 20–24 km one additional fire was missed: SUD42 reported at 0.2 ha.

The largest fire detected was Timmins 13 (TIM13), which was a 135-ha fire with Rank 5 behaviour, which included running, torching and spotting (Fig. S2 in the Supplementary material). The fire was previously known and being aggressively suppressed (but as with all patrols this information was not provided to the crew). The crew noted that they were drawn to the site because of smoke and that no light was initially visible. This was a little unusual because one would normally expect flickering light to be observed before smoke using NVGs.

The inset in Fig. 3 is a NVG image of SUD123, the smallest fire spotted. Unfortunately, because of low ambient light levels on the moonless night there were no good quality NVG images. The night patrol recorded the fire to be 0.1 ha (the minimum reportable size for OMNR fire reports) and Rank 1. Another pass over the area was made during the second sortie; however the fire still proved to be difficult to spot. It took day patrols 2 days to locate and confirm this as a fire.

Fig. 3. Day photo of SUD123 with hand-held GPS device as scale reference. It took daytime patrols 2 days to locate this fire. The inset shows a cropped image of the fire from the patrol.

Mean distances

The average detection distance across all nights was 6678 m (95% CI: 3215–10 140 m). Recall this was the distance at which a decision was made to pursue a light source as a possible fire. The source itself was almost always visible at much greater distances. The average discrimination distance, where a source could be definitively confirmed as a fire or not, was 1618 m (95% CI: 1057–2179 m). There was no significant correlation between detection distance and discrimination distance. Analyses revealed a correlation between the overall discrimination distance and fire size ($r = 0.558$, d.f. $= 19$; $P = 0.013$). However, there was no correlation between detection distance and fire size ($r = 0.254$, d.f. $= 19$; $P > 0.05$).

Signal detection

The number of hits, correct rejections and misses across all nights are shown in Table S3 in the Supplementary material for targets within a range of ±10 km from the planned track and also within ±20 km. There were no false alarms, which occur when an observer falsely confirms a target as a fire.

When considering the occurrence of all fire events (both forest fires and campfires) in relation to the total number of events, the overall specificity is 50%. In other words, of all the events spotted across sorties 50% were actual fires, whereas the other 50% were distractions. For these calculations any event that was not a fire was collapsed into one category. Across all nights there were 70 events in total. Of these, 35 were fires: 20 forest fires (5 new or unreported) and 15 campfires. Correct rejections were defined as any target that was investigated and correctly identified as something other than a fire. The other 35 were correct rejections, most of which were structures.

Size estimates

Size estimates from night patrols were highly correlated with size estimates by day patrols ($r = 0.903$, d.f. $= 16$; $P = 0.001$). Day size estimates were taken from the OMNR's strategic operating plans on the day of the night flight. Day estimates for new or unrecorded fires were taken from the same documents the day after the night flight. Most fire size estimates by the night patrol were close to day estimates. On average the night patrol was accurate to within 0.5 ha. There was no clear trend for night size estimates to be over or underestimated: five fires were underestimated and three were overestimated.

Discussion

Hit and miss rates are not fully representative of a real-life scenario because most spotters in the study were novice observers (students with classroom training on fire detection procedures). Some events were pursued, even though the crew were aware that they were not fires, to help train novice crew members and document common distractions. Although this did not affect the hit or miss rate, decreasing the number of distractions pursued would have allowed more time to be spent detecting fires. If detection had been left to the experienced observers alone, the number of distractions would have been reduced and the hit rate would have likely been higher. The pilots were the most effective observers, but the observers who flew most frequently performed at a similar level to the pilots. In addition, the pilots were the most familiar with the geographical area. Knowledge of the area and experience in both fire spotting and NVG use is critical for improving performance.

In an operational context, with experienced observers who have knowledge of the geographic area, the hit rate would likely be higher. There were a total of 70 targets investigated, of which 35 (50%) were fires (20 forest fires and 15 campfires). Of the forest fires, 5 (25%) were previously unknown to the OMNR. The most common distractions were camps and cottages. Flickering lights from structures beneath the canopy were most likely to be detected and subsequently correctly discriminated from fires. Correct rejections also declined with time, perhaps as observers became more discriminating in which targets they chose to investigate.

General discussion

Strategies and observations

There are no definitive signs for differentiating fires from other sources of light. Ideally, one would use a combination of approaches based on previous fire spotting experience and knowledge of the geographical area. Many light sources appear to flicker from a distance. However, fires usually flicker erratically instead of regularly, as a tower light might. It is important to note that non-fire light sources may at first appear to flicker erratically when in fact they are constant. This often happens with rural structures where the tree canopy may occasionally occlude the light, creating the illusion of flicker. Watching a potential light source for a few moments to see if the flicker becomes steady is one way to avoid false alarms of this nature. Geographic Information System data or experience with the area searched can be useful in discriminating man-made light sources from possible fire sources.

Viewing a light source without the NVGs can also yield important information. Yellow, white or red lights are often signs of artificial lights, whereas fires are often either not visible with the naked eye or are orange in colour. These characteristics are dependent on how far one is from the fire as well as fire size. Nearer the fire, flame and smoke are often visible but smoke is a less reliable cue at night than during daytime detection patrols.

Light sources that appear to move, particularly if also emitting a concentrated beam of light, are usually vehicles (Fig. S3 in the Supplementary material). Vehicles along logging roads can be especially problematic because they travel so slowly it may be difficult to see movement. In addition, logging roads are often narrow, bumpy and lined with trees, increasing the likelihood that the light will appear to flicker erratically. Having a crew member with knowledge of the local area will be a vital resource to eliminate targets on roads and trails.

Once a target has been confirmed as a fire it may be difficult to determine if it is a nascent forest fire or a campfire. Another way to distinguish between campfires and forest fires is in the number of ember beds. Forest fires will, depending on size, have multiple ember beds or smouldering light sources, whereas campfires have only one ember bed. Symmetrically organised light sources of the same size and with halos of the same diameter are probably not forest fires: fires usually display an asymmetrical organisation of lights of varying sizes and brightness.

Because night-time conditions are usually cooler then daytime conditions, forest fires will often appear as smouldering ember beds. This makes them more difficult to detect than open flame or torching trees. In addition, smoke columns, which are useful for fire detection during the day, can be absent or very faint with NVGs. Smoke also often 'lays down' closer to the ground at night. This means that nascent fires at night are often smaller and less immediately visible than nascent fires during the day. On the other hand, new fires started by lightning strikes need time to develop. Further investigation is required to identify the best time of night for NVG aerial detection patrols taking into account visibility, operational constraints, weather, fire indices and fire behaviour.

Safety is another important consideration. NVGs allow pilots and detection observers to see and navigate under low illumination by amplifying available light. However, they do not turn night into day and there are limitations to visual performance using NVGs. For example, the image is monochromatic, noise contaminates the image at low light levels, the unusual spectral sensitivity can result in contrast inversions, and field of view is limited in most devices. These limitations and artefacts presumably underlie the reported deficits in perception of space, depth and motion (for example Sheehy and Wilkinson 1989; Bradley and Kaiser 1994; DeLucia and Task 1995; Braithwaite *et al.* 1998; Hughes *et al.* 2000; Task 2001; Macuda *et al.* 2005). Perceptual issues with NVGs have been counted as a causal factor in military helicopter incidents and accidents in several countries (see Braithwaite *et al.* 1998). Training should take these limitations into account to ensure safe and effective detection patrols.

The image quality of NVGs can be compromised when searching areas that are highly saturated with sources of light. Urban centres and bright light sources should be kept behind the aircraft otherwise they may wash out the image or cause halos (Allison *et al.* 2010). Conversely, overcast or moonless conditions can reduce ambient illumination enough that detector noise becomes an issue in the NVG image (Macuda *et al.* 2005). Under very low light conditions, the image intensifiers in NVGs cause scintillating noise (i.e. a 'grainy' appearance similar to a detuned television) that may influence depth, motion, resolution, form, size and distance perception.

It is important to continually scan the area and take frequent breaks to avoid neck and eye strain (Harrison *et al.* 2007). Scanning the area directly down the side of the aircraft is also valuable because one can see directly down into the tree canopy, decreasing the number of trees occluding a target.

Flight parameters

Over the mixed forest canopy observers found it effective to fly at fairly high altitude (914–1219 m (3000–4000 feet) AGL) during detection, with descent to lower altitude to confirm and characterise the fire. Low-level scanning (305 m (1000 feet) AGL) was not very effective because of unreliable visibility of the fire when hidden by terrain or canopy. Similarly, scanning could be effectively performed at typical cruising speed (e.g. 167 km h^{-1} (90 knots)), allowing efficient coverage with circling or slowing over the fire to confirm and characterise. Helicopters are very flexible in this regard. Very low altitude with helicopters is possible but entails a risk of spreading embers with the rotor wash. In these trials, successful NVG characterisation was possible from 152–305 m (500–1000 feet) AGL. Note that detection with fixed wing aircraft might need different tactics as hovering or low-level circling over the fire is not usually feasible. NVG detection combined with IR characterisation might be effective in this regard.

NVG discrimination of light sources as fires

Detection of fires from the air is easy as even small fires have a strong signal allowing them to be detected. Identifying them as possible fires and then confirming them as such requires approaching to distances of several kilometres. The main issue with discrimination is the variety of competing light sources that must be filtered and eliminated by the observer. Man-made sources, particularly vehicle lights and building or landscape lighting, are the most problematic. This is especially difficult when these sources are partly occluded by canopy so that from the moving helicopter they appear to flicker. Some types of residential and industrial lighting also flicker in the NVG image, although usually the more regular pulsing behaviour can help distinguish these from fires. Campfires are also regularly detected and, although a true fire event, are obviously distractions. Such interference from non-fire environmental sources may limit NVG-aided detection patrols near more heavily populated areas where human activity is expected to be high (which may require later operational windows).

Discrimination proved to be the most difficult part of the task. Although knowledge of the area is critical for determining which targets are worth pursuing, this study showed that novices unfamiliar with the area were still able to detect and discriminate very small fires. Having knowledge of the area will further decrease the number of distractions pursued. NVG detection patrols have potential to be a valuable tool for early fire detection if used in a manner that maximises efficiency, including reliance on user experience, fire intelligence and effective flight path planning.

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Supplementary material

Use of night vision goggles for aerial forest fire detection

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Controlled conditions

Flights and observers

For each flight, detection and classification of fires was performed by a single observer. Over the course of 3 nights of detection testing, 12 observation sorties were flown (five, five, and two sorties on the evening–morning of each of 23–24, 24–25 and 25–26 April). Six observers participated in two detection sorties across different nights with different target fire configuration and locations for a total of 12 sorties. An additional three sorties were flown on 22–23 April to determine suitable ground speed and altitudes for effective detection over the terrain. All observers were trained in fire detection techniques but had no previous experience in fire spotting. Training consisted of the standard fire detection observer training course run by the OMNR, simulations of fire detection scenarios, and instruction on the set-up and use of NVGs.

The flight crew consisted of five or six people: two pilots, an audio/video technician, an experimenter, and the observer (on some flights an additional experimenter tested a tablet based fire logging system but this did not interfere with the main experiment). The *pilots* were the only members of the flight crew aware of the test grid location. However, they were not aware of fire locations and profiles and did not provide any information to the observer. Only the *observers* were responsible for detecting fires and recording them. No other crew member was allowed to assist the observer during a detection flight. The *experimenter* kept a paper log as a backup and marked detection, discrimination and confirmation waypoints and the time of detection. An *audio/video technician* continually recorded audio and video during flights.

Observers filled out a brief questionnaire to indicate the number of hours they had slept and their current level of fatigue. Sorties typically began at 2130 hours each night and continued until ~0200 hours.

After each flight the observer was required to fill out a debriefing questionnaire covering the ability to cover the search area, search strategy, visual performance, spatial orientation, NVG side effects, situational awareness and other factors (see below for details and results pertaining to the debriefing questionnaire).

Apparatus

All flights took place in an EC130 helicopter. A handheld Garmin GPS 96C was used to mark the aircraft location in real time. This unit reported aircraft position every 15 s. The specified accuracy of the Wide Area Augmentation System was less than three meters 95% of the time. In addition, automated flight following data from the aircraft was also obtained. This system reported the aircraft's position every 60 s over a radio link.

Generation III ANVIS 4949 binocular night vision goggles were used. A Canon FS200 recorded video. Audio from the cockpit was fed directly into the camera. The observer entered data on a tablet computer (Toshiba Portege M750, Toshiba Corp., Tokyo, Japan). A custom IR absorbing filter (Korry Nightshield NSX, Esterline Technologies Corporation, Bellevue, WA) was placed over the tablet display to prevent interference with the NVGs.

Plot profiles

The test grid consisted of 109 surveyed locations for precisely located test fires. Based on universal transverse mercator (UTM) coordinate system, the grid was 100 ha with each plot point spaced on 100 by 100-m grid intervals. Canopy density and type of tree coverage varied with each plot and included dense coniferous, dense or semi-dense mixed, and dense or semi-dense deciduous stands. Although it was still springtime, the canopy for the deciduous stands was beginning to fill in, likely due to the mild weather. Elevation of the plots varied between 215 m and 295 m above mean sea level (ASL).

Target fires

On each of the four nights, one to six small test fires were lit at locations within the grid. A total of six simulated fires were lit on 22–23 April (i.e. starting on the night of 22 April and continuing into the morning of 23 April), four fires on each of 23–24 and 24–25 April, and one fire on 25–26 April. Fuels for the test fires were placed in aluminium 30 × 40-cm, fire-proof containers. In many instances, multiple sources were combined in a single plot to simulate a larger fire. Fuel sources were charcoal briquettes (Royal Oak brand, 6.3 × 6.3 × 3.8-cm briquettes; ~60 briquettes lit with starter fluid), artificial fireplace logs (Ecolog Citronella Logs, 30 × 10 × 10 cm, 0.9 kg) and alcohol gel torches (385-mL can).

Fires were monitored visually and through temperature readings made with thermocouples and a data logger. Log fires tended to rise rapidly in temperature shortly after being lit, then gradually decline in temperature throughout the evening; they tended to smoulder much longer than other fires, lasting into the late morning. Charcoal briquette fires typically burned hottest after lighting, presumably due to the open flame and effects of the starter, before entering a phase of approximately exponential decay in temperature. The temperature of torch fires typically increased rapidly then burned uniformly (with spiking and oscillatory fluctuations likely due to wind gusts and variations) before decreasing rapidly. As a result, the torch fires were a well-controlled target until they began to extinguish. The rapid extinction essentially makes these sources both present and stable (on the scale of minutes although flickering on a shorter time scale), or essentially 'out'. However, they were very small and gave off little light, making them the most difficult target to spot.

Ground crews monitored the fires throughout the night; in some instances refuelling was required.

Detection procedure

Each night, a detection route was planned that brought the aircraft near the test grid. In flight, the observer scanned their visible area for potential fires. The observers were the only members of the flight crew responsible for detecting fires. Observers were always seated in the front right seat of the aircraft. This means they were unable to see the areas behind and to the rear-left of their position.

Once the observer spotted a target of interest they notified the pilots and experimenter. The experimenter provided the observer with a waypoint and time, which marked the aircraft's location for target detection. The pilots then deviated from the flight path towards the target. Upon closer inspection the observer either confirmed or rejected the target as a fire. Once again, a waypoint and time was recorded to mark the aircraft location for target discrimination. If the target was confirmed as a fire, its characteristics, such as intensity, size and fuel source were recorded. A final waypoint and time was recorded as the aircraft passed or hovered over the fire to mark the approximate fire location. Once all the required data were recorded the aircraft returned to the original planned flight path. If a target was identified as a bright light but not a fire, the observer attempted to categorise the target

Conditions

During data collection there was a first quarter moon, which provided ample ambient light for NVG use. All observers reported NVG visibility as good and atmospheric conditions were favourable. Unless otherwise stated, calm winds and clear skies prevailed with a visibility of 14 km (9 miles) and wind speeds between 0 and 19 km h^{-1} (0 and 10 knots), gusting to 39 km h^{-1} (21 knots) on one night.

Aerial detection patrols

Materials and methods were generally similar to the controlled experiment with the modifications for operational flights as described below.

Detection patrols

The OMNR continually monitored real-time weather information, forest fuel indices, historical trends and other indices. The flight trials were conducted when the weather and fuel indices were conducive to lightning strike fires. Each night the Aircraft Management Officer planned two detection routes that brought the aircraft over an area that had recently been subject to a large number of lightning strikes. Detection patrols typically flew at an altitude between 914 m (3000 feet) and 1219 m (4000 feet) AGL and at a speed between 111 km h^{-1} (60 knots) and 167 km h^{-1} (90 knots).

Flights typically began at 2230 hours each night and continued until ~0400 hours the following morning. Across groups of flights the moon phase varied from full to no moon. Total flight time was ~27 h and 56 min. A summary of the conditions for the flights is provided in Table S2.

Materials

Materials and apparatus were as previously described for the controlled experiment with the following exceptions: (1) detection activities involved real fires so the controlled sources and dataloggers were not required, (2) most flights took place in an EC130 helicopter; however during one sortie it was necessary to fly in an AS350 and (3) IR still images were taken using a FLIR ThermaCAM P25.

All crew wore Generation III, ANVIS 4949 binocular NVGs.

Flight crew roles

Flight crew complement and roles were similar to the controlled experiment described above; however, all crew members were responsible for detecting fires. The pilots had NVG certification and extensive detection experience. Occasionally it was necessary to fly without an audio–video technician and during three flights there was one pilot instead of two.

In flight, the scanning, detection, discrimination and classification of fires followed the same procedure as the controlled fire trials; however, all crew members now contributed to these tasks and conferred on the decisions. As in the earlier study, GPS waypoint and time were used to mark the aircraft location for target detection, target discrimination as a fire or not and approximate fire location.

Determining ground truth

Unlike the controlled experiment where target fires were known, observers on these flights were looking for real fires in an uncontrolled environment. We were principally interested in (a) hits or the number of fires present along the route that were actually detected, (b) misses or actual fires along the route that were not found and (c) false alarms or reports of fires that did not correspond to actual fires. The difficulty in assessing these numbers is in knowing the 'ground truth'. To estimate hits and false alarms, all fires reported were followed up either by matching to the database of current fires or by visual verification on the ground. Misses were estimated from analysis of fire reports and status for the day of the flight and subsequent days as logged in the OMNR's database. This is likely to overestimate miss rates as fires take time to develop and conversely are sometimes essentially extinguished before being officially declared out. Miss rates were calculated given assumed visibility relative to the flight path with separate estimates of the rates for the reported visibility on the relevant night, a range of ±10 km and a range of ±20 km. The true number of fires in a given range was determined by measuring the distance of active (at the time of the flight) fires from the flight path and tallying fires within the specified visibility range. The hit and miss rates were calculated by dividing the number of forest fires spotted or missed by the total number of forest fires within the range of visibility.

It is important to note that the crew were not informed of the existence or location of existing fires and thus detected fires were truly (new) hits for the detection patrol. Similarly, if known active fires within range of the aircraft were not detected, they were recorded as a miss.

Table S1. Type of distraction for correct rejections and percentage of events that were fires during the 2010 trials over the test grid

	Type of distraction			Classification of events		
	Structure	Vehicle	Unknown	Fire	Other	Fire percentage
23–24 April	7	5	0	10	14	42%
24–25 April	10	2	1	14	14	50%
25–26 April	4	0	1	2	5	29%
Total	21	7	2	26	33	44%
Percentage	70%	23%	7%			

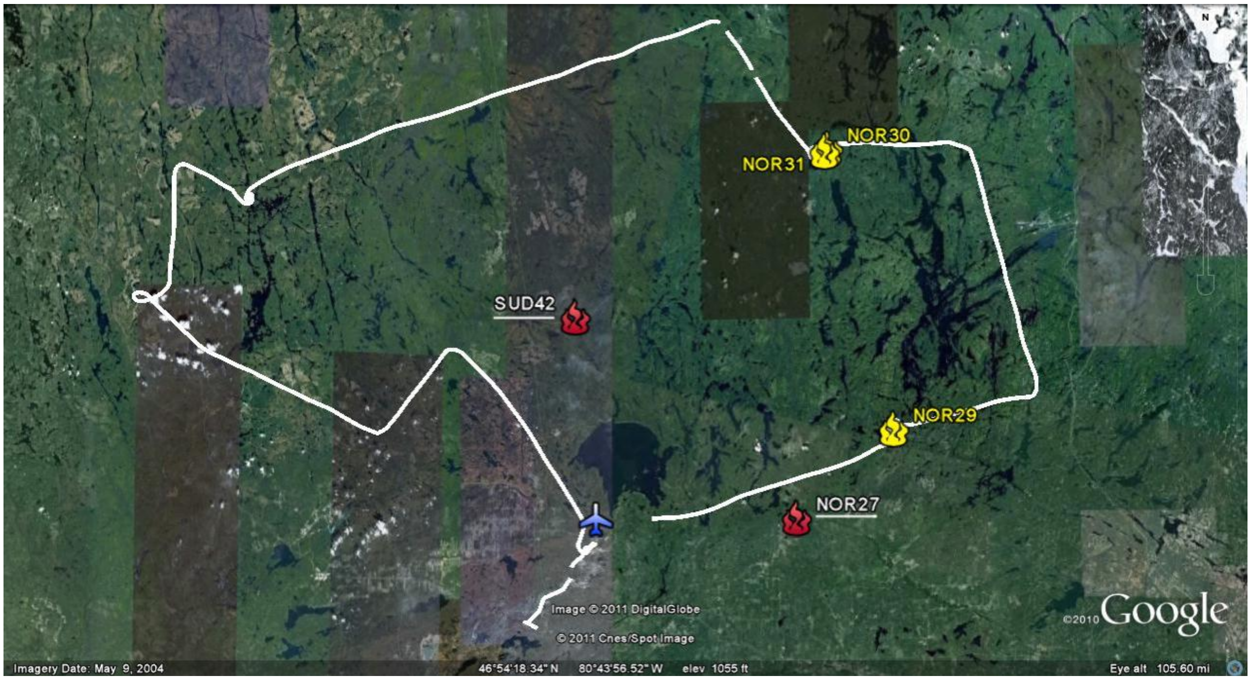


Fig. S1. Google Earth image of flight path and active fires on the evening of 27–28 May 2010. Note this shows actual flight paths rather than planned routes. For each patrol a detection flight path was planned through lightning corridors. Deviations from the planned route are due to targets being identified and subsequently investigated. Found forest fires (hits) are yellow and missed forest fires are red (with underlined labels). NOR30 was located just over 500 m from NOR31. Gaps in track resulted from GPS signal loss.

Table S2. Summary of flight conditions for the 2010 aerial detection patrols

Period (night–morning)	Visibility	Moon	Weather	Sorties	Fires found
27–28 May 28–29 May 29–30 May 30–31 May	24 km	Full	Broken clouds at 2438 m (8000 feet) to unlimited. Air temperature 14–20°C. Dew point 10–12°C. Wind speed 6–19 km h^{-1} (3–10 knots)	7	14
13–14 July 14–15 July	24 km	None, waxing crescent rising after the flights	No cloud. Air temperature 18–25°C. Dew point 11–14°C. Wind speed 6–11 km h^{-1} (3–6 knots).	4	3
7–8 August 8–9 August	24 km 16 km	Waning crescent that rose at 0200 hours and thus absent for two of the three sorties	Broken clouds at 6706 m (22 000 feet) Air temperature 16–19°C. Dew point 10–17°C. Wind speed 6–15 km h^{-1} (3–8 knots)	3	1

Table S3. Signal detection rates for the 2010 aerial detection patrols

Events are pooled across all nights at ±10-km and ±20-km visibility; CR, correct rejection; campfires not included. Miss counts at 20 km are inclusive of misses at 10 km

	Hits	CR	Hit (%)	Miss (%)	Number of misses
10-km visibility	20	35	62.5	37.5	12
20-km visibility	20	35	51	49	19

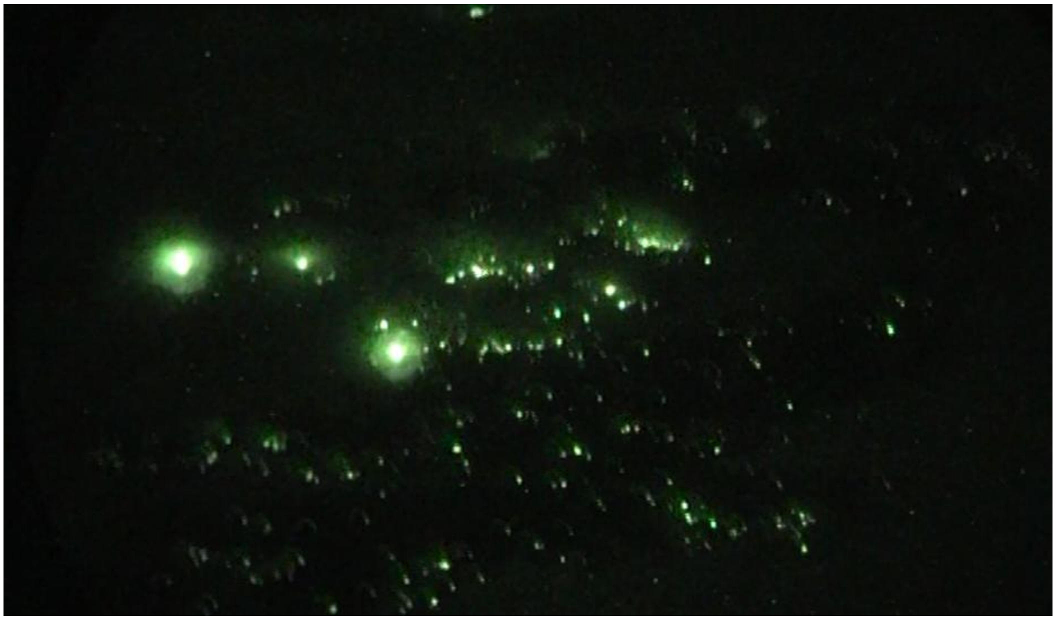


Fig. S2. NVG image of TIM13 on 28 May 2010.

Fig. S3. NVG image of vehicle travelling along a road. Note the beam of light.

Debriefing

After each flight the observer was required to fill out a debriefing questionnaire (see Fig. S4) that consisted of 32 questions covering ability to cover the search area, search strategy, visual performance, spatial orientation, NVG side effects, situational awareness and other factors.

Debrief findings following trials with controlled fires

In the debrief questionnaire, all observers rated their own ability to cover the search area as ‘good’. In addition, they also reported using consistent scanning techniques; the most common technique used was horizontal scanning. Visual performance, spatial orientation and situational awareness were reported as being ‘average’ or ‘good’. One observer reported feeling disorientated when looking up after writing on the tablet to enter the waypoints. It should be noted that several observers were novices to helicopter flying.

Observers were required to rate their confidence in detecting fires on a scale from 1 (not confident) to 5 (very confident). Most observers reported a confidence level of 4, one reported 3 and another 5. In addition, observers reported that both their skills and their confidence in detecting fires increased across sorties. Observers also reported alertness levels both before and after flights on a scale from 1 (not alert) to 5 (very alert). Pre- and post-flight alertness levels were exactly the same for all but one observer, who rated their alertness as 5 pre-flight and 4 post-flight. The most common symptoms experienced during flight were eye strain, headaches and sore necks. Most observers stated that they did not feel over-loaded during the flight. However, one observer reported that recording fire characteristics for four targets situated so close together was difficult. This type of scenario is unlikely to occur in a real operational context because forest fires would not be restricted to such a small geographical area. The most difficult task reported was sifting through the distractions to detect fires.

Both canopy density and altitude were reported as factors affecting task difficulty. A dense canopy made fires more difficult to detect and discriminate. As previously stated, a higher altitude made detection easier, but discrimination more difficult. Most reported that neither topography nor speed affected their performance. However, one observer stated that the hills were more likely to obscure targets at low altitudes. Terrain relief was modest in the vicinity of the trials.

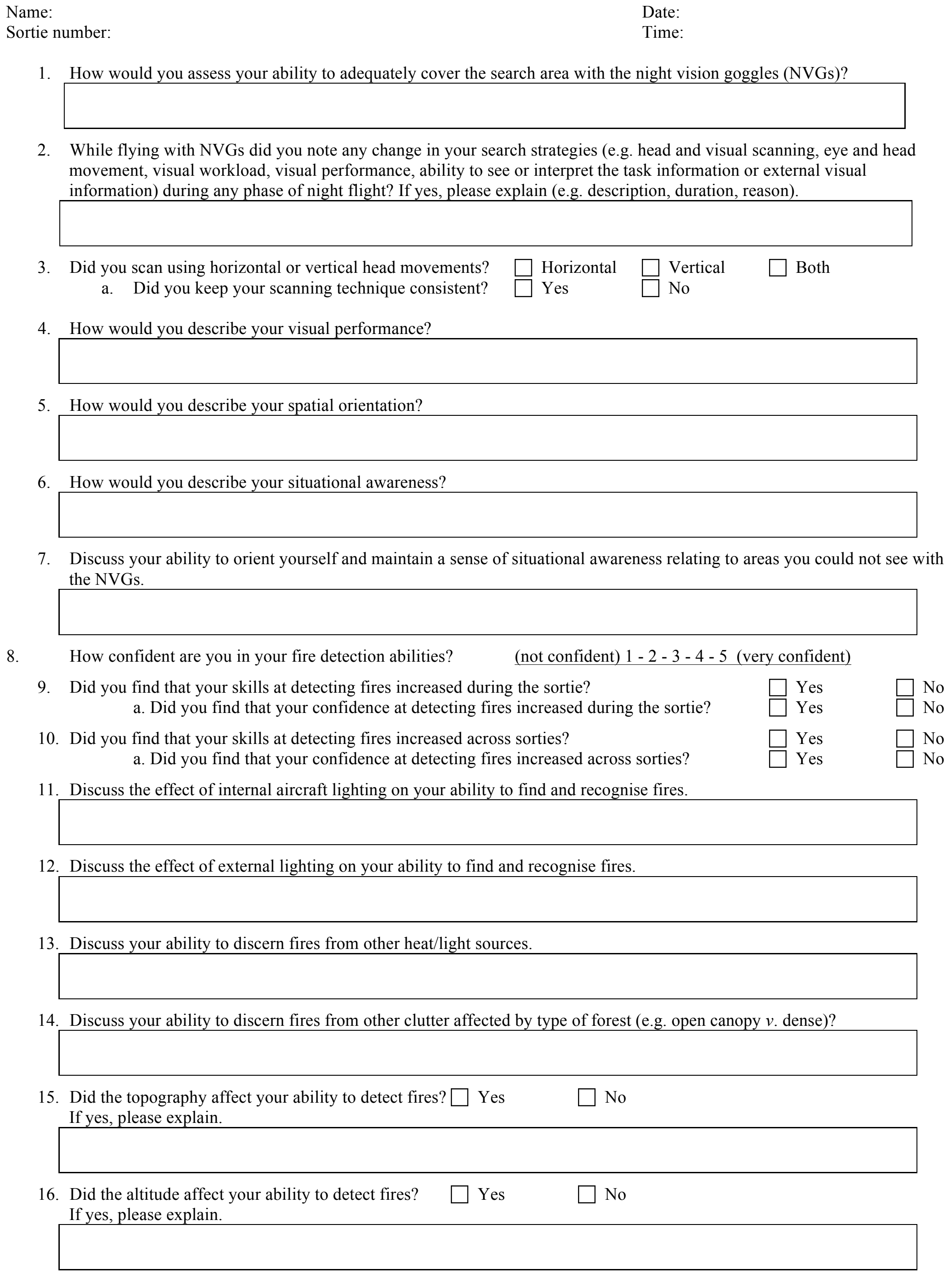
No one reported any problems with internal aircraft lighting. The only reported problem with external lighting was from one observer who stated that the reflection of the moon on the water was distracting. Observers estimated scanning distance to be between 10 and 20 km; weather reports indicated that visibility was 9 miles or 14 km. Both fuel sources and fire intensity rank were visible to all observers; at lower altitude it was easier to determine fire characteristics.

Debrief findings following aerial detection patrols

On the debriefing questionnaire, all observers rated their own ability to cover the search area as ‘good’, except for one observer who reported focussing more on areas close to the aircraft and forward. They estimated that they covered ~80–90% of their search area. In addition, most observers reported using consistent scanning techniques: everyone reported using a mixture of horizontal and vertical scanning. Visual performance was generally reported as ‘good’, but goggle scintillation was noted as present during the July and August flights (on moonless nights). Ability to orient did not seem to be a significant problem and only one observer reported having some difficulty in orienting themselves spatially. Additionally, one observer stated that they had difficulty maintaining situational awareness and often lost track of fires when they were out of sight.

All observers stated that their skills and confidence at detecting fires increased both during and across flights. The exception to this was during the August flights on which both observers stated that they were less confident. This may have been because they found no fires. However, follow-up data show that there were no fires to find along their routes. Alertness levels pre- and post-flight were rated on a scale of 1 (not alert) to 5 (fully alert). Before the flight all observers reported an alertness level of 4 and all but one observer stated that they felt well rested. After the flight, most observers reported a slightly lower alertness level of 3, whereas one observer remained the same. The most common symptoms experienced were eye strain, headaches and sore necks.

Observers reported that a dense canopy made fires more difficult to detect and discriminate. Consistent with observer reports from the controlled experiments, higher altitudes allowed for more effective detection but lower altitudes were required for discriminating fires. In all cases fuel stands and open flame were reported as visible from the air.



Name: Date:
Sortie number: Time:

1. How would you assess your ability to adequately cover the search area with the night vision goggles (NVGs)?
2. While flying with NVGs did you note any change in your search strategies (e.g. head and visual scanning, eye and head movement, visual workload, visual performance, ability to see or interpret the task information or external visual information) during any phase of night flight? If yes, please explain (e.g. description, duration, reason).
3. Did you scan using horizontal or vertical head movements? ☐ Horizontal ☐ Vertical ☐ Both
    - a. Did you keep your scanning technique consistent? ☐ Yes ☐ No
4. How would you describe your visual performance?
5. How would you describe your spatial orientation?
6. How would you describe your situational awareness?
7. Discuss your ability to orient yourself and maintain a sense of situational awareness relating to areas you could not see with the NVGs.
8. How confident are you in your fire detection abilities? (not confident) 1 - 2 - 3 - 4 - 5 (very confident)
9. Did you find that your skills at detecting fires increased during the sortie? ☐ Yes ☐ No
    - a. Did you find that your confidence at detecting fires increased during the sortie? ☐ Yes ☐ No
10. Did you find that your skills at detecting fires increased across sorties? ☐ Yes ☐ No
    - a. Did you find that your confidence at detecting fires increased across sorties? ☐ Yes ☐ No
11. Discuss the effect of internal aircraft lighting on your ability to find and recognise fires.
12. Discuss the effect of external lighting on your ability to find and recognise fires.
13. Discuss your ability to discern fires from other heat/light sources.
14. Discuss your ability to discern fires from other clutter affected by type of forest (e.g. open canopy *v*. dense)?
15. Did the topography affect your ability to detect fires? ☐ Yes ☐ No
    If yes, please explain.
16. Did the altitude affect your ability to detect fires? ☐ Yes ☐ No
    If yes, please explain.

Fig. S4. Debriefing questionnaire.