COMPUTING AERIAL SUPPRESSION EFFECTIVENES BY IR MONITORING.

Eulalia Planas[1], Elsa Pastor[1], Yolanda Pérez[1], Matt Plucinski[2] & Jim Gould[2]
[1]*Center for Technological risk Studies, Universitat Politecnica de Catalunya, Barcelona, Spain.*
[2]*Bushfire Dynamics and Applications, CSIRO Sustainable Ecosystems, Canberra, Australia.*

ABSTRACT

This document describes the methodology developed to analyse the IR images obtained during the aerial suppression experiments that were conducted in Ngarkat Conservation Park, South Australia, on 3rd - 5th March 2008. This methodology has been specifically developed in order to be able to extract the maximum information from the IR images taken from an observing helicopter, in those tests were chemical suppressants are applied directly on the fire, although it could eventually be applied to other similar situations. The information obtained after applying this methodology allows quantifying the aerial suppression effectiveness.

INTRODUCTION

Mediterranean climate has shaped fire prone environments not only located in the Mediterranean Basin but in many other areas around the world. Typical shrub dominated vegetation together with forests of high flammability species are also present in North and South America, South Africa and Australia. The protection of such ecosystems against the fire is a challenge for the scientific community who aim to provide suitable tools i.e. guidelines, meters, models, simulators, etc. to assist fire management. For that, a sound understanding of both fire behaviour and suppression difficulty is required.

During the last decades, some outstanding experimental programs have been conducted in such landscapes to obtain good fire data for developing or validating fire management tools [1]. The most recent example found in that direction corresponds to project FuSE (Bushfire CRC Australia), where three large experimental campaigns were executed between 2006 and 2008 [2]. The main milestone of this project is to develop a fire behaviour model and a prescribed burning guide to assist land management agencies to plan and safely conduct actions for effective hazard reduction and ecological sensitive management in mallee-heath vegetation in South Australia. In order to achieve these goals the experimental program of FuSE project was designed to reach several particular objectives. They were to characterise the fuel properties and structure over time; define the combination of fuel structure and fire weather conditions that will sustain the propagation of fire; the fire behaviour associated with South Australian mallee-heath vegetation; and finally, compare the effectiveness of different aerially applied fire suppressants. The framework of the study reported in this paper corresponds to this last objective and has as experimental scenario the aerial suppression effectiveness tests developed within the FuSE project.

The term suppression effectiveness can be difficult to define and has received various interpretations and measures in the literature [3], for the purposes of project FuSE it was considered in four contexts:

- Productivity, in terms of line construction rates.
- Placement, in terms of location of the drop with respect to the target

- Coverage, in terms of adequate coating of the critical fuel (i.e. the fuel that may support the fire spread)
- Effects on fire behaviour, in terms of fire intensity extinguished, fire progression slowed and suppression holding times.

Although IR imagery could help in quantifying the productivity, the methodology developed aims at quantifying only the drop placement, coverage and effect on fire behaviour. We can call this the drop effectiveness. Table 1 gives a list of some key questions that have to be answered when dealing with drop assessment. All the listed aspects need to be considered in relation to the suppressant agents being used, the fire fighting tactics and strategies being employed, and the aircraft and delivery systems that are available.

Effectiveness context	***Key questions***
Placement	▪ Has the drop reached the intended target? ▪ Was this the most appropriate target? ▪ Has the drop reached the best orientation? ▪ Which is the position of the drop in relation to the fire edge? ▪ Has the drop been linked well with its preceding drop?
Coverage	▪ Did the drop penetrate through the canopy and into the fuels? ▪ Was there adequate coating of surface and near surface fuel layers? ▪ Were there gaps in the coverage? ▪ Was there enough coverage between linked drops?
Effects on fire behaviour	▪ Has the drop been breached by spotting? ▪ Has the drop been burnt around? ▪ Has the drop been burnt through? ▪ Has the drop holding time lasted enough? ▪ Has the fire intensity been reduced to the level required? ▪ Has the fire been slowed/stopped?

Table 1: Major considerations for drop assessment.

To make a systematic analysis of the effectiveness of aerial suppression drops on fires, a high quantity of data on suppression drop characteristics, fire behaviour and fuel characteristics is needed. These measurements are very difficult to undertake on real fires due to the chaotic nature of wildfire events, so this sort of high quality information can only be collected from planned experiments. There have already been a few attempts to collect such sort of data. In [4] and [5] a summary of the most significant ones can be found. Among them, two contributions have to be highlighted for their extent and resources devoted; the first being developed during 1983 and 1984 by the USDA Forest Service under the Operational Retardant Effectiveness (ORE) program [6] and the second in Australia during 1984-1985 by the CSIRO under the Project Aquarius [7].

The use IR for monitoring field applications during field experiments has been recently reported in [8]. These experiments did not include suppression tests. However, the experimental methodology concerning IR monitoring, obviously helped by the enormous improvement of IR technology over recent years, provided an optimum description of a fine-scale variability in fire behaviour.

The main objective of the present study was to analyse and quantify at fine scale the effectiveness of several chemical suppressants drops delivered by fixed wing aircraft in operational fire conditions using airborne IR imagery. The work reported in this paper describes the development of the methodology generated to record and analyse IR images. This entails the experimental methods used at the field, the pre-processing effort to transform the IR images into proper views of the fire edges, the analysis of the drop position and characteristics and the criteria to calculate fire behaviour variables to give a quantitative description of the suppressant effects.

EXPERIMENTAL SITE AND EQUIPMENT

The experimental area was located in Ngarkat Conservation Park, in eastern South Australia. This reserve (270000 ha) comprises a mosaic of shrub and woodland vegetation that experiences high intensity fires almost annually, threatening an important number of flora and fauna in serious danger of extinction.

The experiments took place on three large plots within 20 year old woodland dominated by multistemmed eucalypts (mallee). Mallee woodlands are made up of short (2 to 10 m) trees with shrubby understory. The surface fuel and suspended bark fuel are the main fuel layers that carry the flame front [2]. They are concentrated around the base of individual eucalypts leaving very little fuel in the gap between the tree clumps and thus making up a highly discontinuous fuel complex.

The experimental plot layout can be seen in Figure 1. The research plots were roughly flat and with rectangular shape and were named AS1 (around 720 m x 760 m), AS2 (around 650 m x 750 m) and AS3 (900 m x 1000 m) in the image, they all covered more than 45 ha. An airbase with mixing facilities and an air strip was set up close to the eastern site of the experimental areas in order to reduce turnaround times.

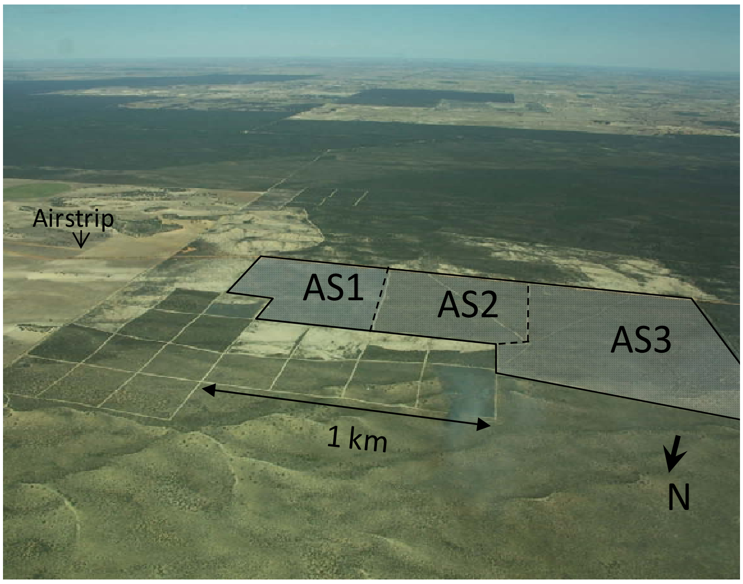


Figure 1. Experimental layout of the aerial suppression experiments.

The experiments were designed to test three different suppressants, one in each plot. In AS1, a super absorbent polymer based gel was planned to be tested being applied directly on the fire edge concentrated on head and flank fires, while a foam based suppressant was used in AS2. In AS3 long term retardant based on diammonium phosphate was laid out in lines 200m ahead of the ignition line prior to ignition.

Two main data collection roles were planned for the experiments, the first being ground investigation during and after the fire where researchers would attempt to locate the drop sites, making fire behaviour observations and recording fire activity. The second data source was aerial monitoring. An Infrared (IR) camera (AGEMA Thermovison 570-Pro, FLIR Systems) and a visible camera operated from an observing light helicopter were used to monitor fire behaviour and suppression during the experiments. The IR camera operated within the 7.5-13 μm range and was equipped with a frame grabber to control and store sequences of IR images (240 x 320 pixels) from a laptop computer at a rate of 5 fps. Every IR image is in fact a 240 x 320 cells temperatures matrix which is represented by a colour map gradient. More details about the technical characteristics of the IR can be found in [9]. The cameras were positioned in the helicopter on top of a fixed tripod and hand-held operated, which allowed optimising the focus on the fire evolution. Apart from tuning the equipments, some extra work has to be done prior to each experiment. A number of contained bonfires (in half 44 gal drums) fuelled with mallee roots and coarse woody material had to be burning in known locations around the plots to serve as geo-references for the image analysis.

Finally, complementary information was expected to come from other sources such as fire behaviour and weather observations and measurements, GPS tracking systems installed in the aircraft, airbase samples and incidental observations and photographs.

PERFORMANCE OF THE AERIAL SUPPRESSION EXPERIMENTS

The experiments were conducted on 3rd – 5th March 2008. This period of the year coincides with the last part of the summer, when extreme weather conditions for high intensity fires can still occur. In Table 2 the meteorological conditions recorded during the test are summarized.

	03/03/2008 AS1 experiment (Gel)	***04/03/2008 AS3 experiment (Retardant)***	***05/03/2008 AS2 experiment (Foam)***
Maximum Temperature, ºC	35	32	37
Minimum Relative Humidity, %	8	23	13
Wind speed (Gust), km/h	16(35)	19(33)	19(33)

Table 2. Meteorological conditions during the tests.

The fires were ignited with 200 m drip torch lines perpendicular to the predominant wind direction to allow them to grow quickly. The aerial fire attack did not start until the fire perimeters were greater than 400 m. Nevertheless, the monitoring task started as soon as the ignition time was reached. The desirable location of the helicopter was hovering at a stationary position along the plot edge parallel to the fire spread, advancing following the head of the fire. The optimum flying height was such to have in the same field of view all the geo-references and the fire and drops activity with the maximum resolution. It ranged between 500-800 m, depending on the experiment. It has to be highlighted that meeting these requirements was sometimes difficult due to wind shifts and turbulences. Finally, the observation aircraft and cameras were positioned to avoid highly oblique images within the dropping footage.

METHODOLOGY TO ANALYSE THE IR IMAGES

The methodology described in this work has been specifically developed in order to extract the maximum information from the IR thermography images taken during aerial extinction operations where chemical suppressants are applied directly on the fire edge. The methodology described here applies to a single drop; if more than one drop have to be analysed, this methodology will have to be applied as many times as drops included in the study.

The methodology can be divided into two main parts, every of which comprises several steps (Figure 2). The first part is centred on the location of the drop zone while the second part is devoted to the procedures to obtain the characteristic parameters of the drop and its evolution over time. To show how the methodology has been created, data from a particular test (AS2) has been used.

Part I: Location of the drop zone on the IR images

– Step 1. Identifying t_{di} and t_{df} for each drop.
  The first step of the methodology is to identify, for every drop, the time within the IR sequence at which the drop starts (t_{di}) and the time at which the drop has been completely laid onto the ground (t_{df}).

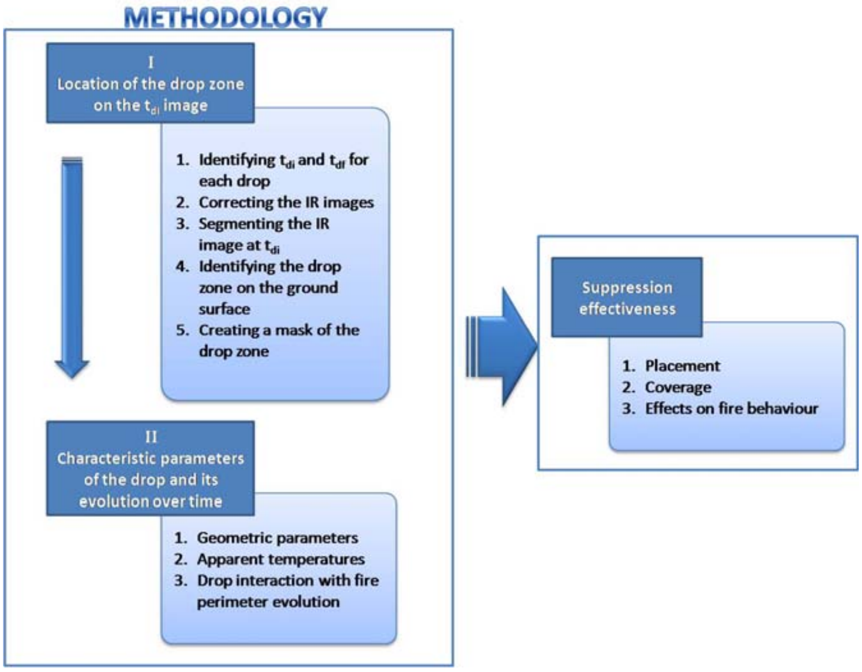


Figure 2. Scheme of the developed methodology.

– Step 2. Correcting the IR images.
  Every single image of a given IR sequence that will be used in the analysis has to be corrected in order to obtain the orthogonal view of it. To do this correction a homography matrix is created using 4 reference points of the IR image, for which the real GPS coordinates are known (i.e, the corners of the plot, the contained bonfires or in some cases the ignition line). Then, the homography matrix is calculated by a direct linear transformation [9].

– Step 3. Segmenting the IR image at t_{di}.
  In aerial monitoring, the temperature values measured by the IR camera can not be considered as real temperature values (for this reason from now on, it will be named apparent temperatures). This is due to the high distance between the camera and the fire and therefore to the great amount of radiation absorbed by the atmosphere. However, the temperature range provided by the camera can be split into several segments, so that diverse characteristic zones can be distinguished (i.e. preheating, flaming, glowing, residual, burned and unburned zone) according to the state of the fuel. To define these areas threshold temperature values have been assigned to each segment (Table 3).

– Step 4. Identifying the drop on the ground surface.
  The temperature gradient between t_{di} and t_{df} has been used to identify the area where the drop has a significant effect in terms of temperature reduction. This area will be considered the study area, and from now on it will be called the *drop zone*. The temperature gradient has been computed as the difference between the apparent temperatures matrix IR(t_{di}) and IR(t_{df}), divided by IR(t_{di}). A different temperature reduction is expected depending on whether the action of the chemical suppressant is taking place for instance on a flaming zone –where the

temperature may fall hundreds of degrees–, on unburned fuel–where the temperature decrease detected by the IR camera will be less than 10ºC. Thus, in order to select the drop zone, a threshold gradient value has been defined for the segmented zones and for the possible interfaces between zones which have been detected the drop could reach (Table 3).

Characteristic zone	**IR temperature value (K)**	**Temperature gradient (%)**
Flaming	> 700	25
Glowing	600 - 700	25
Residual/ Preheating	425 - 600	15
Burned	360 - 425	10
Unburned/cooled	< 360	10

Table 3. Threshold temperature values for the characteristic zones.

Part II: Characteristic parameters of the drop and its evolution over time

Once the drop zone has been located, numerous parameters can be obtained either at the instant in which the drop has reached the ground (t_{df}) or observing its evolution over time:

– Geometric parameters
  Area covered by the drop zone (either in pixels or m^2); maximum length and width of the drop zone; drop zone area covering burned, flaming, glowing, residual or unburned zones (either in pixels, m^2 or percentage of the total drop zone area)

– Apparent temperatures
  Maximum, minimum and mean temperatures in the drop zone at t_{di} (i.e. before the drop), at t_{df} and afterwards.

– Drop interaction with fire perimeter evolution
  Interaction of the drop with the fire perimeter in order to obtain the holding time and to see if the drops has been burnt around, through or breached by spotting.

RESULTS AND DISCUSSION

Herein the results obtained for one of the drops in plot AS2 are presented in order to illustrate the methodology developed. Plot AS2 was burned on March 5th under south-westerly and westerly winds and a total number of twelve foam loads were dropped during the burning of this plot. The drop selected for the current analysis is drop 2.

IR images corresponding to the instants t_{di} and t_{df} for drop 2 can be seen on Figure 3. The fire spreads wind-aided from west to east (from the right side of the image to the left). To make images more understandable at a glance, plot borders and the drop location on the left flank (square symbol), have been outlined on them.

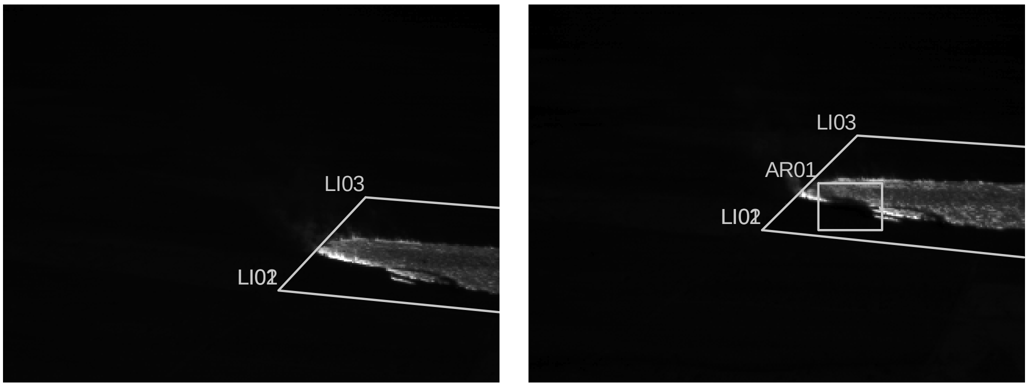


Figure 3. IR images corresponding to the instants t_{di} and t_{df} for drop 2 (plot AS2).

The location of drop 2 has been obtained by applying the methodology described before. Figure 4 shows the drop zone (filled area) overlapped on the temperature contours map of the corrected IR image corresponding to the instant t_{di}. On this figure each unit of the x-axis and y-axis is equivalent to 3 meters. Once the drop zone has been located, drop pattern characteristics are computed. In this case, the drop zone is about 3400 m^2, 180 m in maximum length and 68 m in maximum width.

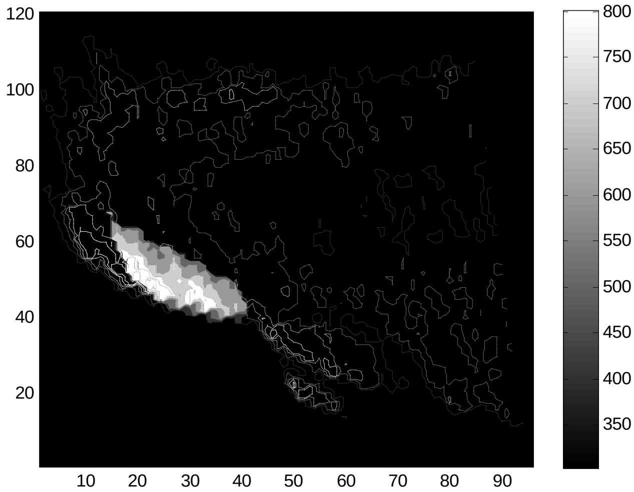
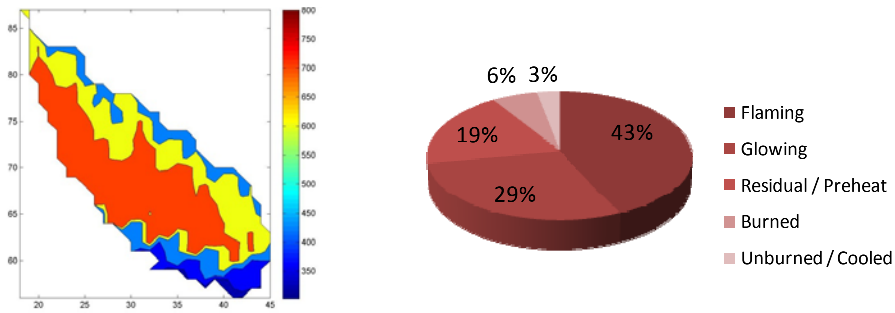


Figure 4. Apparent temperature contours of the IR images at t_{di}, where the filled area corresponds to the drop zone.

According to Table 3, the different zones identified within the drop are calculated at t_{di} and t_{df}. As it can be seen in Figure 5a, the zone reached by drop 2 was mostly in flaming and glowing combustion just prior to the foam delivery.

a)



b)

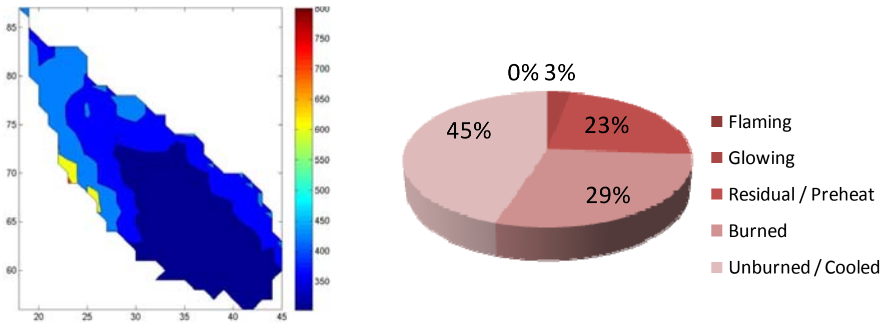


Figure5. Percentage of the drop zone area covering flaming, glowing, residual, burned and unburned zones and their position in the drop zone. a) Instant t_{di}. b) Instant t_{df}.

Concerning the residual/preheating fraction (19%), a detailed observation of the fire front evolution has to be done in order to distinguish between both categories. In this case roughly half of this percentage can be attributed to the residual zone (the upper side of the drop zone) and the other half to the preheating (the area situated just below the flaming combustion zone). The immediate effect of the foam, when reached the ground, was the nearly extinction of the flaming and glowing combustion (Figure 5b), which have been reduced to less than 1% and 3% respectively.

The analysis of the evolution of the apparent temperatures on the drop zone allows the study of the foam effect over time. This analysis can be performed paying attention either to the mean, maximum and minimum apparent temperatures at the drop zone (Figure 6). As it can be observed, temperature drops suddenly when the product reaches the ground, but experiences an increase 75 seconds after, which lasts until the second 150 approximately, meaning that something is happening inside the drop zone.

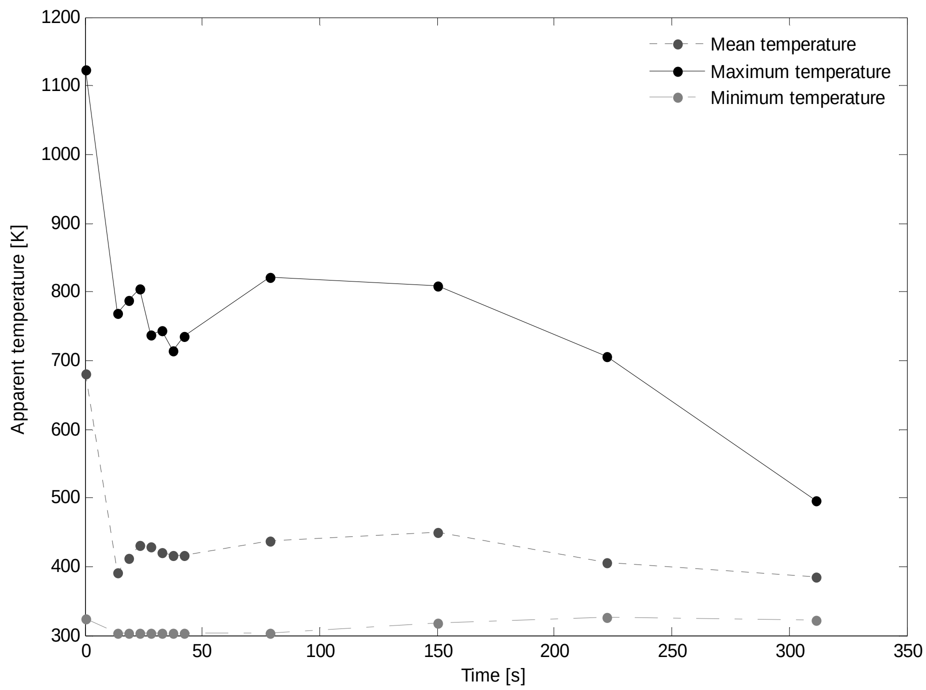


Figure 6. Maximum, minimum and mean apparent temperatures in the drop zone over time.

In order to analyze what happens during the period between the second 75 and 150 a study of the interaction of the drop zone with the fire perimeter has been done (Figure 7).

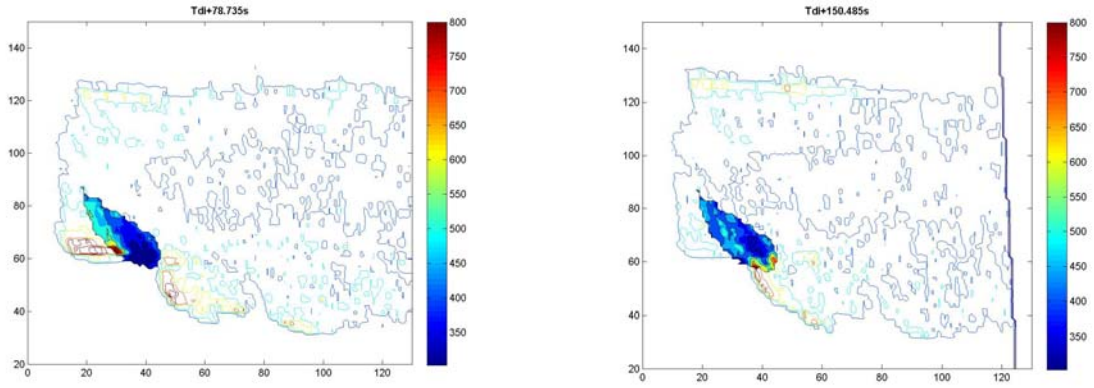


Figure 7. Apparent temperature contours of the IR images, where the filled area corresponds to the drop zone. A) Image at $t_{di\,+\,78.73s}$, b) Image at $t_{di\,+\,150.49s}$

For example, in Figure 7a it can be observed that the flaming and glowing regions that remained after the drop delivery were significant enough to keep the fire spreading on the left edge of the drop zone (from t_{df} to $t_{di+78.74s}$), consuming part of the fuel that was being preheated on the instant t_{di}. The image at $t_{di+150.49s}$ (Figure 7b) shows that some other flaming and glowing regions appear. This is due to the effect of a finger fire coming from the back of the left flank which consumes the unburned fraction of the drop.

CONCLUSIONS

A methodology to quantify aerial suppression effectiveness in terms of placement, coverage and effect on fire behavior, at fine scale by means of airborne IR images has been developed. The methodology has shown to be reliable and powerful in the analysis of large fire scenarios. It can be extrapolated to diverse situations (chemicals and delivery tactics, fuel complexes and topography) given the needed georeferences. The results shown in the paper allow seeing the wide range of drop characteristics that can be obtained which makes this method a promising tool.

ACKNOWLEDGEMENTS

This research is supported by the Spanish Ministry of Education and Science under the projects AGL2005-07269 and AGL2008-01161. It is also supported by the Commission for Universities and Research of the Catalan government, the European Social Fund and the Technical University of Catalonia (UPC). The experiments were supported by the South Australian Department for Environment and Heritage, the South Australian Country Fire Authority, the Victorian Department of Sustainability and Environment and the Bushfire Cooperative Research Centre. We also wish to thank the many fire fighters and research staff who assisted with the experiments.

REFERENCES

[1] Viegas, D.X., Palheiro, P.M., Pita, L.P., Ribeiro, L.M., Cruz, M.G., Ollero, A., Arrue, B., Dios. R.M., “Analysis of Fire Behaviour in Mediterranean Shrubs: The Gestosa fire Experiments (Portugal)*”. Proc. of the V International Conference on Forest Fire Research,* Figueira da Foz, Portugal. (2006).

[2] Myers, J., Gould, J., Cruz, M.G., Henderson, M., “Fuel dynamics and fire behaviour in Australian mallee and heath vegetation” *USDA Fores Service Proceedings* RMRS-P-46CD (2007).

[3] Cumming, S.G. “Effective fire suppression in boreal forests”, *Canadian Journal of Forest Research*, 35, 772-786 (2005).

[4] Giménez, A., Pastor, E., Zárate, L., Planas, E., Arnalods, J.," Long-term forest fire retardants: a review of quality, effectiveness, application and environmental considerations". *Int. J. Wildland Fire* 13:1-5 (2004).
[5] Agueda, A., Pastor, E., Planas, E., "Different scales for studying the effectiveness of long-term forest fire retardants", *Prog. Energ. Combust.* 34: 782-796 (2008).
[6] George, C.W., "An operational retardant effectiveness study", *Fire Management Notes* 46(2):18-23 (1985).
[7] Loane, I.T., Gould, J.S., "Aerial suppression of bushfires. Cost-benefit study for Victoria". CSIRO Publishing Report (1986).
[8] Mc Rae, D.J., Jin, J.Z., Conard, S.G., Sukhinin, A.I., Ivanova, G.A., Blake, T.W.,"Infrared characterization of fine-scale variability in behaviour of boreal forest fires". *Can J. For Res.* 35: 2194-2206 (2005).
[9] Pastor, E., Àgueda, A., Andrade-Cetto, J., Muñoz, M., Pérez, Y., Planas, E., "Computing the rate of spread of linear flame fronts by thermal image processing", *Fire Safety J.* 41:569-579 (2006).