Validation of MODIS and AVHRR Fire Detections in Australia

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Abstract
The Sentinel Bushfire Monitoring System is an internet-based mapping tool which provides timely spatial information to fire agencies across Australia. The mapping system allows users to identify active fire locations that pose a potential risk to communities and property. Sentinel at Geoscience Australia currently provides hotspot information derived from Moderate Resolution Imaging Spectroradiometer (MODIS) and Advanced Very High Resolution Radiometer (AVHRR) sensors on a continent-wide and daily basis enabling the fire community and general public to locate active fires. There has been little validation undertaken of the Sentinel since the system began operating in November 2002. Validation datasets have been collected for this work during the 2003-2007 fire seasons. Five study areas were selected to validate the detection capabilities of the MODIS and AVHRR hotspot product with fire activity that was mapped using high resolution earth observation imagery. The objective is to evaluate the reliability with which hotspots identified in MODIS and AVHRR thermal data can be used to identify fires. This consists of comparing the accuracy of AVHRR versus MODIS and quantifying the accuracy of both products. This objective is achieved by characterising errors through a stratified random sampling technique establishing a relationship between the 'fire' and 'no fire' condition, and error assessment using multi- source reference datasets over coincident MODIS and AVHRR pixels. The validation framework comprised two key approaches including validation of AVHRR hotspots in relation to MODIS hotspots and validation of both MODIS and AVHRR hotspots using multi-sensor earth observation imagery datasets. The study identified sources of errors associated with the Sentinel hotspots which could be used to improve the performance of hotspot algorithms and provide user-friendly information for the users. Statistical analysis revealed that overall commission errors of MODIS and AVHRR hotspots over the 5% sample data were 15% and 68% respectively, and overall omission errors of MODIS and AVHRR hotspots were 17% and 23% respectively. An important outcome of this study is the production of a database of fire locations derived from high-resolution imagery, which can serve as a resource for future validation efforts as detection algorithms evolve and sensors change.

1. Introduction

Increasing efforts are being directed to produce comprehensive fire products such as hotspots at a national/global scale. Hotspot is an area with elevated thermal spectral response on an airborne or satellite image. There are two major fire mapping systems in Australia that include the Sentinel Bushfire Monitoring System (https://hotspots.dea.-ga.gov.au) and the Firewatch (https://srss.landgate.-wa.gov.au/fire.php). These fire mapping systems generate fire hotspot information from NOAA and MODIS sensors to provide timely spatial information to fire agencies across Australia. The mapping system allows users to identify active fire locations which are a potential risk to communities and property. A collaborative project between the Defence Imagery and Geospatial Organisation (DIGO), CSIRO Land and Water and Geoscience Australia (GA) led to the implementation of the Sentinel national bushfire monitoring system in 2002, for detection and monitoring of bushfires in Australia. The system has been operated by Geoscience Australia since 2005.

Key requirements for Near Real Time (NRT) detection and monitoring of fires consist of frequent observations and rapid mapping of hotspot locations at a national scale at least on a daily basis. The fire

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detection algorithm must be fast (within an hour of acquisition), robust, accurate and automatic (without human intervention) in order to implement control measures. Ahern et al., (1998 and 2001) noted that these requirements meet the needs of key users including regional/global change research community, policy and decision makers as well as fire and emergency managers. The speed of obtaining and disseminating fire information is underpinned to a large extent, by the fire monitoring systems (Gregoire et al., 2000 and Ahmad and Alkhatib, 2014). However, the accuracy of fire information is a common issue for the users. This paper will address the accuracy of Sentinel Bushfire Monitoring as users continuously demand accurate product delivered rapidly.

The accuracy of fire detection is calculated in terms of commission and omission errors as well as error distributions over various locations (Forghani et al., 2007a). Commission and omission errors have been reported by users and this validation work aims to characterise and assess the accuracy of Sentinel hotspots. Errors of omission represent "failure to detect fires" and errors of commission represent "false alarms or false positives" pixels identified as fires. The focus of this paper is accuracy assessment of the Sentinel MODIS and AVHRR hotspots. To facilitate discussion about accuracy of fire detection, we provide an overview of Sentinel bushfire monitoring system and relevant literature. This paper describes work to quantitatively assess the accuracy, in terms of rates of commission and omission errors, of MODIS and AVHRR fire hotspot detections in Australia as produced by the Sentinel system. This type of research is a valuable contribution to the data environment supporting fire management in Australia, particularly as it makes recommendations for the improvement and future validation of the Sentinel system (Grang, 2009).

1.1 Geoscience Australia's Sentinel Bushfire Mapping System

The Sentinel system accesses data from the MODIS and AVHRR satellites. MODIS (on Terra and Aqua) obtain images of Australia four times a day (twice during the day and twice during the night). MODIS has 36 spectral channels at three spatial resolutions, 250m in two channels (red and near infrared (NIR)), 500m in five channels (going from blue to short wave infrared (SWIR) and one km at the remaining 29 channels (ranging from blue to thermal infrared (TIR).Collecting data at three different spatial resolutions, each MODIS instrument views almost every point of the Earth approximately twice daily with a viewing swath of more than 2,330 km. Their improved spatial resolution and spectral calibration offer low cost, high quality data for active fires studies. MODIS data offer a larger dynamic range of radiance values (12-bit quantization) than AVHRR data (10-bit quantization), thereby reducing the saturation problem associated with fire detection of AVHRR. The raw image data is received by Geoscience Australia's Data Acquisition Facility at Alice Springs. The data is processed to create a surface temperature image known as the MOD14 product. Hobart gives duplicated coverage of Eastern Australia, and extends coverage to New Zealand. The MODIS data is processed to detect hotspots applying a contextual algorithm (Giglio et al., 1999). Fires are identified by flagging pixels in the MODIS data where the temperature value exceeds threshold values (~300K. Principally, the algorithm uses the strong emission of mid-infrared radiation from fires (Matson and Dozier, 1981). It examines each pixel of the MODIS swath, and ultimately assigns each pixel to one of the following classes: missing data, cloud, water, non-fire, fire or unknown. Sentinel uses radiance (brightness) temperatures* (Rybicki et al., 2004) in the 4 µm and 11 µm bands for detection of hotspots. The algorithm developed by the University of Maryland/NASA detects hotspots if $T4 - T11 \geq 20K$ (10K for night passes) and $T4 > 320K$ (315K for night passes), where, T4 and T11 represent brightness temperatures in Kelvin derived from MODIS bands 22 and 31 respectively (Kaufman et al., 1998). Hotspots exceeding the threshold value of 305 K will be detected by Sentinel. MODIS channel 22 saturates at 335 Kelvin and channel 21 saturates at about 504 Kelvin.

The AVHRR sensor on-board the NOAA 17 and 18 satellites cover 1.09 km² AVHRR pixel at nadir, using two thermal bands in the spectral range of 10.3 µm to 11.3 µm and 11.5 µm to 12.5 µm. The AVHRR bands 3B (3.55 - 3.93 µm) and 4 (10.30 - 11.30 µm) are the most useful region of the electrometric spectrum for hotspot detection in which fires appears as bright pixels. The AVHRR channel suitable for fire detection is the mid-infrared channel. Radiation is measured in five distinct wavebands. The visible channel 1 and near infrared (NIR) channel 2 measure reflected solar radiation whereas the thermal channels 4 and 5 measure emitted thermal infrared.

* Brightness temperature is the temperature a black body in thermal equilibrium with its surroundings would have to be to duplicate the observed intensity of a grey body object at a given frequency (https://en.wikipedia.org/wiki/Brightness_temperature).

Channel 3, in the mid infrared, is a hybrid and sensitive to a combination of both reflected and emitted radiances (Hay, 2000). This channel is highly sensitive to objects which are emitting thermal energy at high temperatures (290 Kelvin), e.g. vegetation fires. The algorithm cannot detect fires through thick cloud or smoke. Sentinel maps hotspots from AVHRR band 4 and 3B using a fully automated contextual algorithm (Giglio et al., 1999 and Giglio, 2009) that was modified to Australian environment by Rogers et al., (2006). The use of AVHRR in addition to MODIS not only increases hotspot observations per day but it builds redundancy in case of a MODIS sensor failure.

1.2 Relevant Studies

Hotspot detection algorithms and the science of fire detection have been widely discussed by Lee and Tag (1990), Justice et al., 1993, Flasse and Ceccato (1996), Setzer and Malingreau (1996), Chu et al., 1998), Giglio et al., (1999, 2003, 2008, 2009), Giglo (2007 and 2009), Kushida, (2006), Li et al., (2001), Morisette et al., (2002), Rogers et al., (2006), Molina-Pico et al., (2016), Lutakamale and Kaijage, (2017), Mubarak et al., (2018) and Jang et al., (2019), Gibson, et al., (2020), and FIRMS, (2021). Most hotspot algorithms use fixed thresholds applied to single or multiple bands of thermal IR data for both MODIS and AVHRR sensors and contextual analysis of the pixel and its background (Li et al., 2001). Limitations exist with fixed threshold algorithms including the need to specifically tune thresholds for each application to encompass unique environmental conditions (Gautama *et al.,* 2008). Other limitations include the inability to detect small low intensity hotspots (Wang and Smith, 2007). In the MODIS version 3 active fire detection algorithm's sensitivity to small fires was sacrificed to reduce false alarms over certain surface types during the day (Justice et al., 2002). The MODIS 4, contextual fire detection algorithm was enhanced which increased the ability to detect small cool fires (Giglio et al., 2003). Wang et al., (2007) further formulated an improved algorithm from the MODIS version 4 contextual algorithm to improve the algorithms ability to capture small cool fires. Evaluation of the MODIS active fire product to quantify detection rates of both Terra and Aqua MODIS sensors was carried out by Hawbaker et al., *(*2008). Finding, MODIS had the ability to capture large fires in the US, but may under represent fires in areas with high cloud, rapid burning or small and low intensity fires.

Extensive validation of the MODIS active fire products has been carried out by Justice et al., (2002), Giglio et al., (2003), Morisette et al., (2005) Csiszar et al., (2006), Schroeder et al., (2008) and Hawbaker et al., (2008) and Turner et al., (2012) at various scales. Justice et al., (2002) concluded that under the ideal conditions a fire of 0.005 ha can be detected with near 100% probability. However, there is limited validation in Australian landscapes. Furthermore, a review of the literature revealed insignificant quantitative validation of Sentinel hotspots had been undertaken in Australia (Forghani et al., 2007 and 2014). Three major associated factors are access to limited ground truth validation data, affordability of high resolution data and funding issues for field data collection (Setzer and Malingreau, 1996). Consequently, there is a need for a systematic quantification of the accuracy of both MODIS and AVHRR hotspot products in Australia. Fire detection accuracy (errors of commission and omission and their distribution) is also important from the users' perspective. Studies by Liew et al., (1998), Loboda and Csiszar (2006), Hyvarinen (2006) and Nakau et al., (2006) highlighted that AVHRR derived fire products in general tended to overestimate burnt area/hotspots whereas MODIS hotspots products tended to slightly underestimate burnt area/hotspots.

Liew et al., (1998) validated MODIS and AVHRR fire spots using SPOT 4 data over Sarawak in Malaysia and Sumatra in Indonesia; they concluded that most fires detected by SPOT were detected by MODIS also while some small fires detected by MODIS were not detected by SPOT. The AVHRR exhibited high commission errors. They suggested applying adaptive thresholds to overcome commission errors present in hotspots. Wooster et al., (2003) used an adaptive thresholding approach to detect potential hot pixels containing active fires from bi-spectral infrared detection (BIRD) imagery (thermal infrared at 10µm). Wooster et al., (2003) implemented hotspot detection algorithm developed by Zhukov et al., (2005) which was tested over BIRD imagery in Sydney. Also, Hyvarinen (2006) compared fires detected from 2002 to 2005 by the Finnish detection system for AVHRR imagery and the MODIS based system developed by NASA and the University of Maryland. The research found very few fires greater than 10 ha detected by satellite can be matched with in-situ observations of forest fires.

Furthermore, Nakau et al., (2006) compared detection of hotspots from AVHRR and MODIS satellite imagery over boreal forests in Alaska and Siberia employing field data collected by fire fighters and aerial surveys. A detection accuracy of 46.5% was reported when comparing ground observation and hotspots detected from AVHRR imagery. Other studies such as Hiavka and

Livingston (1997) and Hiavka and Dungan (2002) investigated the effects of pixel size and model based corrections for increasing the accuracy of areal estimates of fragmented cover types. They degraded fire scar thematic maps derived from a European Remote Sensing Satellite (ERS-1) image with a 12m pixel spacing to a 100m and degraded fire scar thematic maps produced from a Landsat MSS image with 57m pixel spacing to 250 MODIS map. They used an approach similar to Oleson et al., (1995) and Moody and Woodcock (1996) who applied MODIS and Synthetic Aperture Radar (SAR) images to produce coarse resolution maps at 250m and 100m respectively. In this regard, the coarse resolution maps are simulated by degrading the fine resolution map directly, rather than degrading the original image and classifying it.

Rogers et al., (2006) implemented hotspot detection algorithm developed by Giglio (2007) algorithm for Geoscience Australia Sentinel for AVHRR hotspot products. A preliminary validation exercise indicated that the system captures 85% of hotspots. Their study was undertaken over limited areas in Queensland, the Northern Territory and Western Australia. A detailed assessment of Sentinel hotspots is therefore required. Davide Ascoli et al., (2014) developed a method to linking genetic algorithms (GA) to the Rothermel fire spread model. They validated GA randomly to create solutions of fuel model parameters to form an initial population. Solutions are then validated against observations of fire rate of spread via a goodness-of-fit metric. They showed that GA improved the performance of the Rothermel model in three published custom fuel models for litter, grass and shrub fuels and recommended that GA may be considered as a viable method to calibrate custom fuel models in fire modelling systems based on the Rothermel model.

2. Validation Method

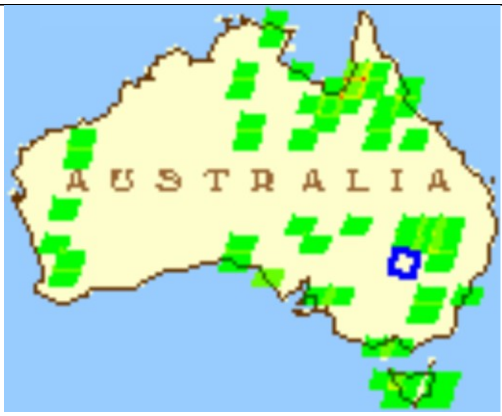
The study consists of two key approaches: validation of AVHRR hotspots using MODIS hotspot data and validation of both MODIS and AVHRR hotspots using high resolution imagery such as ASTER and Landsat data. We used the datasets listed in Table 1(a and b) to validate the system as shown in Figure 1.

Table 1a: Validation datasets

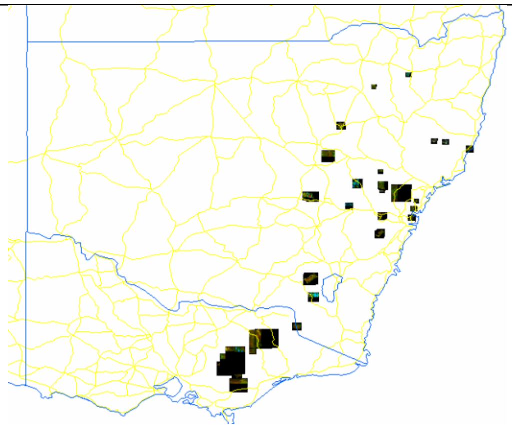
Fire Validation Datasets	**Source**	**Location**	**Comments**
Daedalus 1268 Airborne Thematic Mapper (ATM)	NSW Rural Fire Services (NSWRFS)	Eastern Australia	18 scenes
ASTER	Geoscience Australia	Australia wide	12 scenes (Table 1b)
Landsat 5 and 7	Geoscience Australia	Australia wide	14 scenes
MODIS	Geoscience Australia	Australia wide	28 scenes,
NOAA	Geoscience Australia	Australia wide	25 scenes
Fire polygons	NSW Rural Fire Services Sydney		ESRI shapefiles
Sentinel website (MODIS and NOAA hotspots)	Geoscience Australia	Australia wide	ESRI shapefiles
Firewatch website (MODIS and NOAA hotspots)	Firewatch Perth	Western Australia and Northern Territory	Comparison only
Field information	NSW Rural Fire Services Illawarra	Wollongong and Illawarra	Photographs of fires

Table 1b: Parameters of ASTER and Landsat 7 data used to validate the Sentinel hotspots from the MODIS active fire

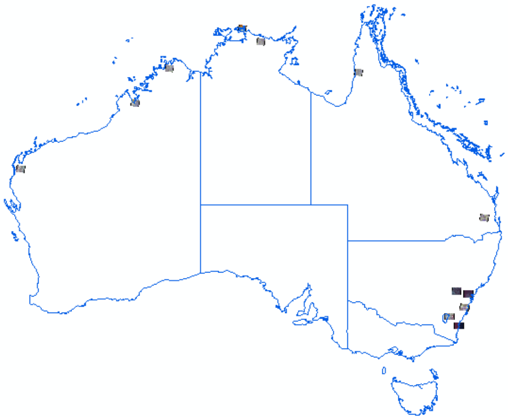
Terra ASTER	ASTER Coverage		Coincident Landsat 7
Date and Time	Centre Latitude	Centre Longitude	
2003-11-15 00:24:46	27d21'00" S	147d46'47" E	
2003-11-11 23:54:21	29d12'36" S	153d10'12" E	
2003-09-28 00:25:34	33d06'43" S	145d39'35" E	
2003-08-08 01:27:13	**12d21'36" S**	**133d57'35" E**	**2003-08-08 00:58:49**
2003-07-30 01:33:02	11d15'35" S	132d25'47" E	2003-07-30 01:05:04
2003-05-07 01:59:46	14d35'59" S	126d28'12" E	
2004-10-19 00:50:44	14d55'53" S	141d56'44" E	2004-10-19 00:38:23
2004-09-30 01:59:42	17d30'07" S	123d40'06" E	
2004-09-17 23:58:50	**27d05'32" S**	**152d13'31" E**	**2004-09-17 23:30:45**
2004-09-08 02:38:22	23d00'27" S	114d17'48" E	2004-09-0802:58:21
2004-02-05 00:12:51	28d21'35" S	150d15'36" E	
2005-03-13 00:00:57	**34d35'24" S**	**150d37'37" E**	



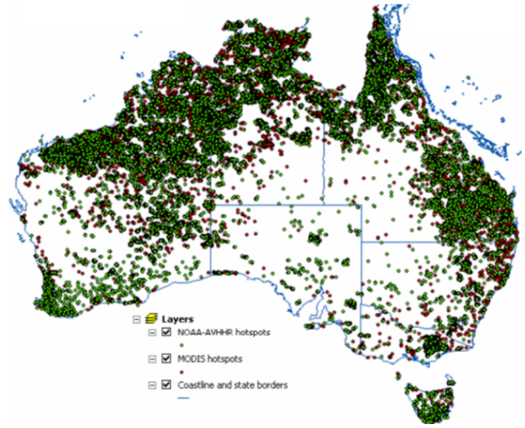
(a) Spatial distribution of coincident Landsat imagery searched from GA earth observation archive over the fire season



(b) Spatial distribution of coincident NSWRFS airborne scanner imagery over during the fire season



(c) Spatial distribution of coincident ASTER imagery over the fire season



(d) Spatial distribution of AVHRR and MODIS hotspots in the fire season

Figure 1: The spatial distribution of selected coincident imagery for analysing active fires in 2006-2007

2.1 Validation of AVHRR Hotspots Using MODIS Hotspots

In order to assess AVHRR hotspot detection performance, the following process was used:

- Daily hotspots derived from night passes of AVHRR and MODIS data covering the period from October 2006 to February 2007 were collected. The time difference between selected MODIS and AVHRR passes is about two hours. For consistency, those AVHRR or MODIS hotspots beyond the two hour difference of their detection time were excluded from the analysis.

- Spatial analysis was applied to select AVHRR hotspots using a buffering technique to compensate for differences in geolocational accuracies between two sensors. The New South Wales Rural Fire Services (NSWRFS) fire polygons digitised from airborne imagery and field information were also used in the spatial analysis process.

- The number of hotspots from each sensor were compared in to order provide a basis for selection of required reference earth observation imagery (TM, ETM+, ASTER, and NSWRFS airborne datasets) for areas with high commission and omission errors (Figure 2).

A comparison of hotspots from AVHRR and MODIS observations indicates that there are about 49.5% of AVHRR hotspots which match with MODIS hotspots. Given relative accuracy of MODIS hotspot products in comparison to AVHRR hotspots data (e.g. Liew *et al.,* 1998, Ichoku *et al.,* 2003, Loboda and Csiszar, 2006, Hyvarinen, 2006, Nakau *et al.,* 2006 and Gautam *et al.,* 2007), and applying high confidence level (80-90%) of the MCD14ML product (Figure 2c), it was found that about 50% of AVHRR hotspots are accounted as false alarms.

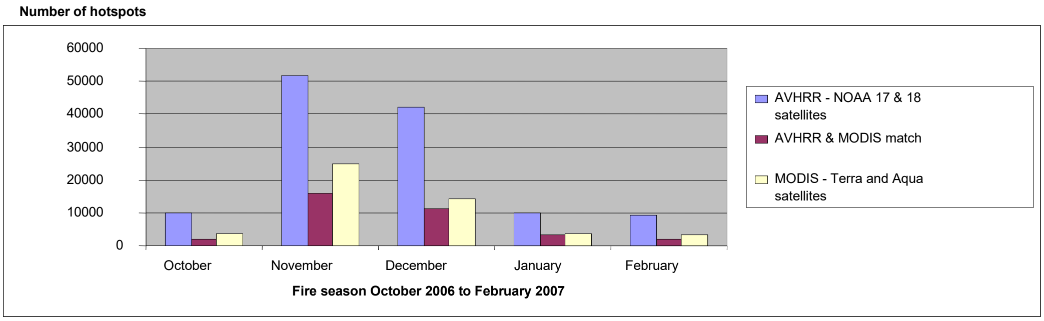


Figure 2a: Summary of analysed hotspots for the fire season

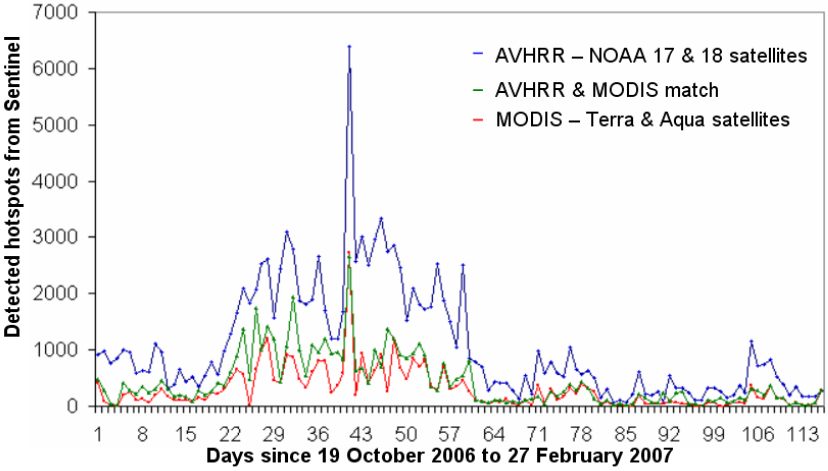


Figure 2b: Relative accuracy of AVHRR hotspots compared with MODIS hotspots detected by Sentinel throughout Australia each day during the 2006-2007 fire seasons

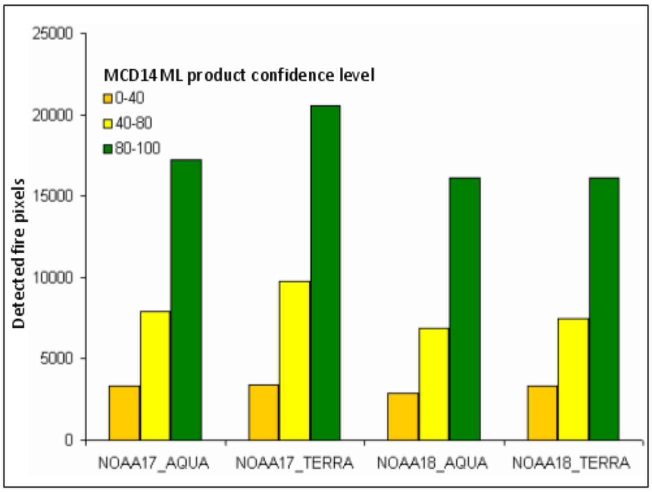


Figure 2c: Comparing relative accuracy of AVHRR hotspots with MODIS hotspots using confidence level from MODIS Collection 5 active fire product

The months of November and December (days 26 to 61) experienced the highest commission errors as shown above (Figure 2a and 2b). The cause of this will be discussed in a later section. On 28 October 2006 for example, AVHRR detected 1114 hotspots compared to 310 hotspots by MODIS. Of the 1114 AVHRR hotspots, only 118 hotspots detected by AVHRR were spatially coincident with MODIS. In addition, on 29 November 2006, AVHRR detected 6381 hotspots compared to 2665 hotspots by MODIS. Of the AVHRR 6381 hotspots, only 2727 hotspots detected by AVHRR were spatially coincident with MODIS. In these two examples, commission errors of AVHRR hotspots are mainly located in southern and eastern Australia. Locations with the largest omission and commission errors were studied in detail using high resolution earth observation imagery.

2.2 Validation of Hotspots Using High Resolution Earth Observation Imagery

2.2.1 Random sampling

Accuracy assessment of the entire hotspots database demands significant resources (imagery, ground survey data and staff). Reducing the number of observations was achieved through random sampling. This study divided the hotspots into three subgroups (strata) and took a simple random sample in each subgroup based on some characteristic which were decided according to the major variables being studied (Yates, 1960). This involved selection of 5% of MODIS and AVHRR hotspots from the total hotspots population for the fire season using a stratified-random sampling (proportional or quota random sampling) approach followed by error estimation (within 5% sample population) supported through a range of imagery sources. An advantage of stratified sampling over simple random sampling is that it enables representation of both the overall population and key subgroups of the population, especially small minority groups. For this study, the variable of interest is the geographical location of hotspot and the stratification factor that will be the geographic latitude ranges influencing the fire characteristics. We used three strata based on regions (latitude) as shown in Figure 3: hotspots located in region 1 (10°S, 20°S), hotspots in region 2 (20°S, 30°S) and hotspots in region 3 (30°S, 43°S). Random samples were then selected from each stratum. The same proportions are selected within each stratum, making the sample a proportionately stratified random sample. Taking inappropriate, inadequate, or excessive sample sizes adversely influences the quality and accuracy of study. Based on the guidelines for sampling produced by Cochran (1977) and Bartlett et al., (2001) 5% of hotspot samples from AVHRR (3265) and MODIS (3135) from the fire season population of 65,315 and 62,698 hotspots respectively were generated at random, in a stratified manner, using the R programming environment (http://cran.r-project.org/).

2.2.2 Error assessment using airborne data

Generally, airborne campaigns/surveys are logistically expensive and may not be possible for an endeavour such as this work due to organisational priorities. However, this study took advantage of airborne scanner data acquired by the NSWRFS (Cotterill, 2007). The spatial resolution of these data varies from 6m to 11m and offer sufficient spatial detail for locating fire pixels.

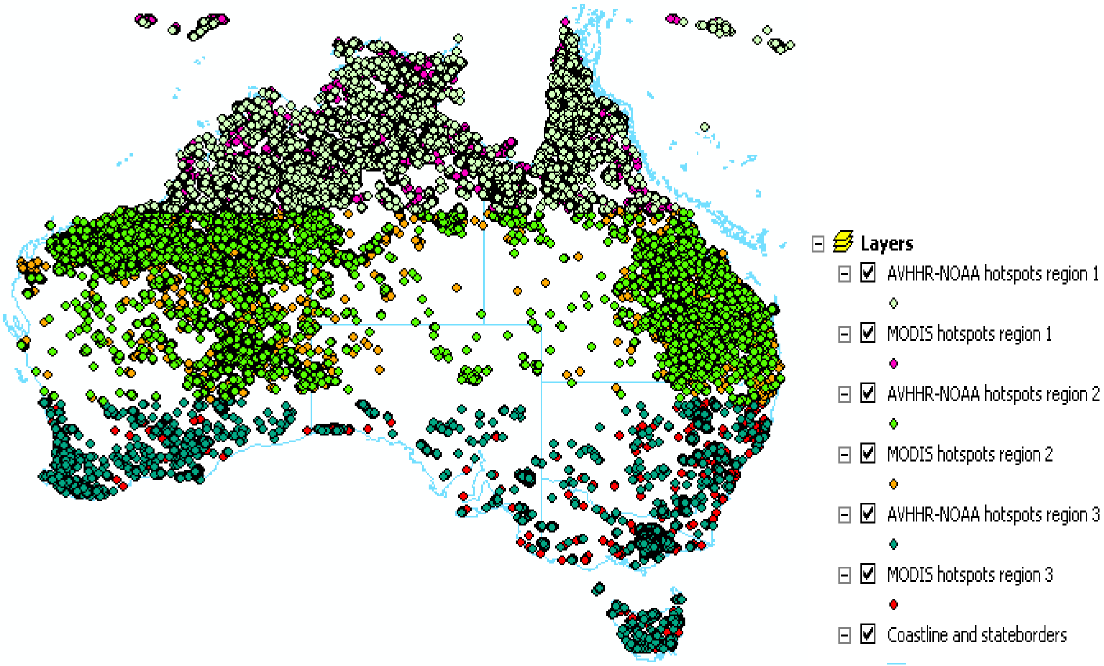
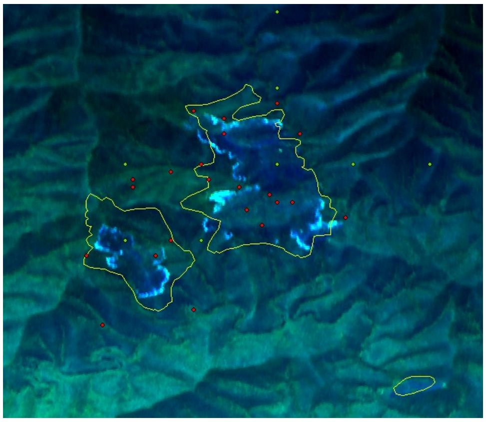
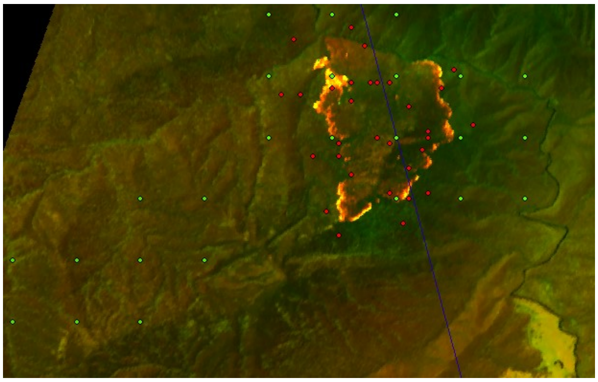


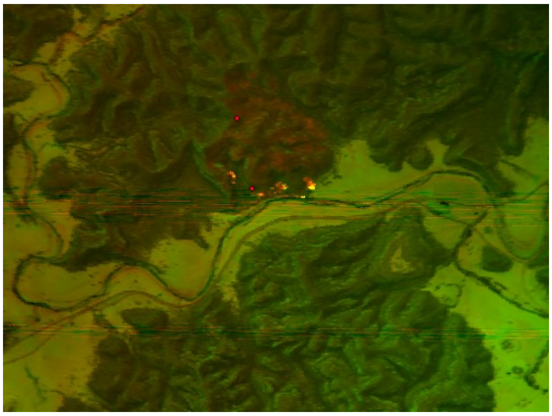
Figure 3: Stratification of MODIS and AVHRR hotspots into three regions



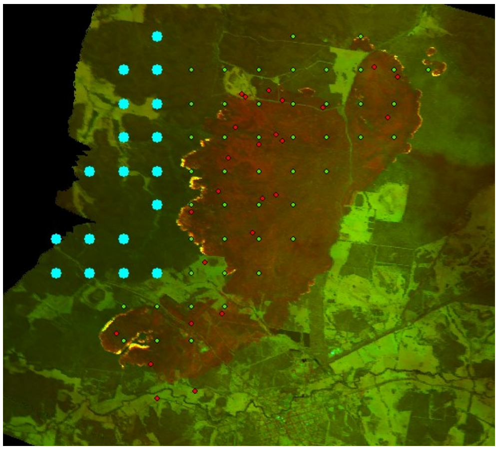
MODIS and AVHRR hotspots are shown in red and green respectively, and the small polygon on the bottom right shows fire polygon about one km^2 (yellow) indicating a small fire is detected by neither MODIS nor by AVHRR



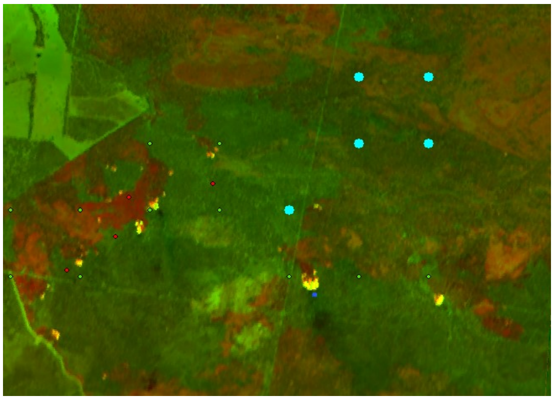
MODIS and AVHRR hotspots are shown in red and green respectively. There are a number of false AVHRR hotspots that are related to threshold values of hotspot detection algorithm



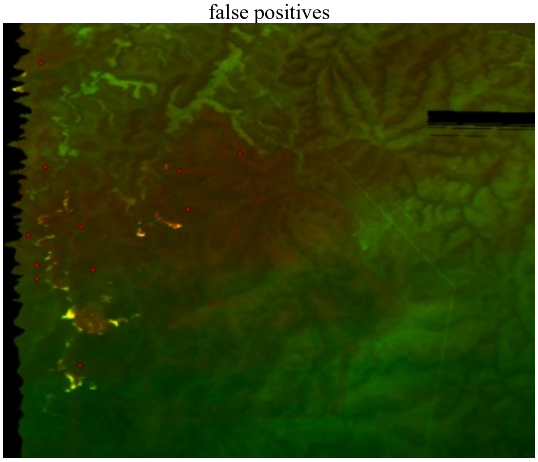
MODIS hotspots (red) are superimposed on airborne image and no AVHRR hotspot is detected due to the size of fire (0.24 km^2)



MODIS hotspots (red) are superimposed on airborne image and AVHRR hotspots are shown in green and cyan that cyan dots are false positives



Commission error of AVHRR hotspots (cyan) and MODIS hotspots (red); area of each fire is about 0.20 - 0.95 km^2. MODIS failed to detect these fires while they were detected by AVHRR (green)



Omission error of AVHRR hotspot and presence of MODIS hotspots (red); areal size of each fire is about 0.24 - 0.9 km^2

Figure 4: Examples of omission and commission errors of AVHRR and MODIS hotspots using airborne imagery. Note: the hotspots (dot points) shown are not to scale

A hotspot was selected as 'true' fire if it satisfied the following conditions: (a) it falls within one of the perimeters of the burnt-area polygons; (b) its thermal brightness temperature (290° to 338 Kelvin for AVHRR, and 305 to 504 Kelvin for MODIS), (c) there must be an obvious trace of smoke plume emanating from the fire, and (d) area of fires is equal or greater than one km^2. Figure 4 provides examples of omission and commission errors of AVHRR and MODIS hotspots using reference airborne scanner data.

2.2.3 Error Assessment Using ASTER Imagery

Imagery from Landsat 5 and 7 and ASTER play a key role due to their low cost, their intermediate scale and their wider coverage (relative to airborne scanner data). Comparative analysis of the ASTER and Landsat 7 data was carried out to validate hotspots over a number of regions in Australia coving a total area of 375,025 km^2. In Figure 5(a-c), the MODIS 1000m grid is overlaid on ASTER 15m data and provides information on wind speed and direction from the smoke plumes emanating from hotspots in the snap-shot image. The smoke plume dispersion pattern shows a south-easterly wind direction. Figure 5(c) which is an examination of thermal and multispectral MODIS data reveals that there is a significant spatial miss-registration (up to approximately 3800m) between the Sentinel hotspots with the fire scars seen on ASTER data. Figure 5(d and e), show the ASTER thermal band 14 (10.95 - 11.65 µm) 90m pixel was acquired on 8th August 2003 and indicate the fire front as series of bright spots.

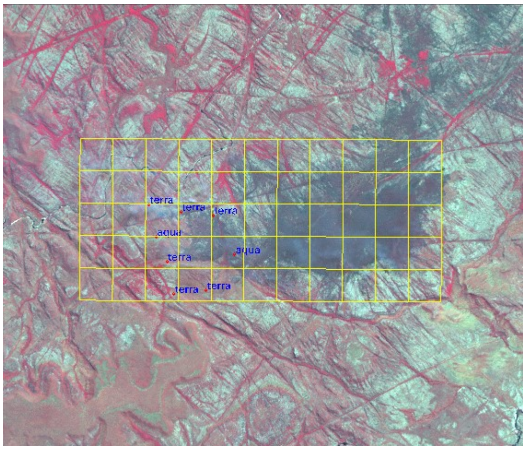
3. Discussion and Results

Accuracy assessment of Sentinel hotspots was done in order to identify the types of errors and their distribution. Fires which occurred in a two-hour window on the same date were buffered when distance between them was less than 0.003-0.015 degrees. The accuracy assessment results agree well with the spatial analysis methods applied to hotspots from the two sensors. However, MODIS underestimated active fires by 23% on MOD14 product that includes fire-mask, algorithm quality, radiative power, and numerous layers describing fire pixel attributes. MOD14 products typically will fail to detect fires roughly smaller than half a pixel size of the sensor at one km data (~50 ha).

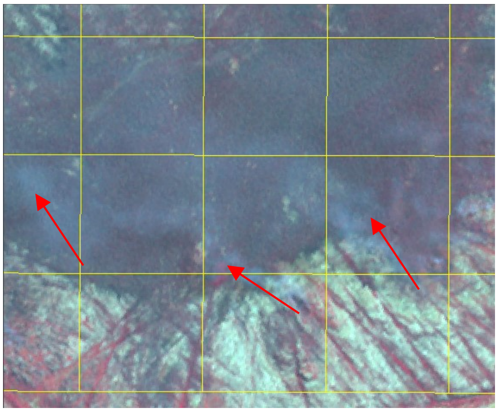
The geolocational accuracy of GA's MODIS products was assessed by Wang and Smith (2003) using Landsat products and they found that the products were within 200m and 800m for Terra MODIS and Aqua MODIS respectively. The MODIS, ASTER and Landsat footprints and the hotspots were superimposed on the reference images. Examination of thermal and multispectral MODIS data reveals significant discrepancy in spatial location (1800m to 3800m) of the assessed hotspots with the fire scars seen on ASTER data. Quantitative assessment suggests that most hotspots detected from MODIS have high correspondence to the fires mapped in ASTER and Landsat data. It was found that the MODIS Sentinel active fire detection algorithm performed well with low commission (false alarm pixels) error rate but had a higher omission (undetected active fire pixels) error rate over most regions of Australia in the absence of cloud cover.

The analysis of a large number of high resolution earth observation datasets highlighted a number of error sources including sensor malfunction, black out (pixel drop outs) in imagery, anthropogenic heat sources, surface temperature, fire spread rate, clouds cover, amount of smoke and wind direction, etc). As an example, occurrence of hotspots over the Port Kembla steel factory areas near Wollongong is dependent on the plant's operational activities and varies from date to date. This is a typical error of classification in that it is a hotspot with an elevated spectral response which is being identified correctly but the response should not be classified as a fire. A database of features such the Port Kembla Steel works linked to the Sentinel would be useful to refine the hotspots presented on the Sentinel. During this study it became obvious that there are a small number of anthropogenic heat sources (e.g. plants, factories, and industrial resources/infrastructure generated heat) that are fixed in position and almost continuous in their presence throughout urbanised areas. A database of these sources, their location, and time of operation, temperature and size may provide the opportunity to filter out the false hotspots from real active fires leading to an improvement in the accuracy of identifying hotspots detected from the satellite passes. Information about the behaviour of these targets would be useful for applications such as calibration and validation of sites in the future.

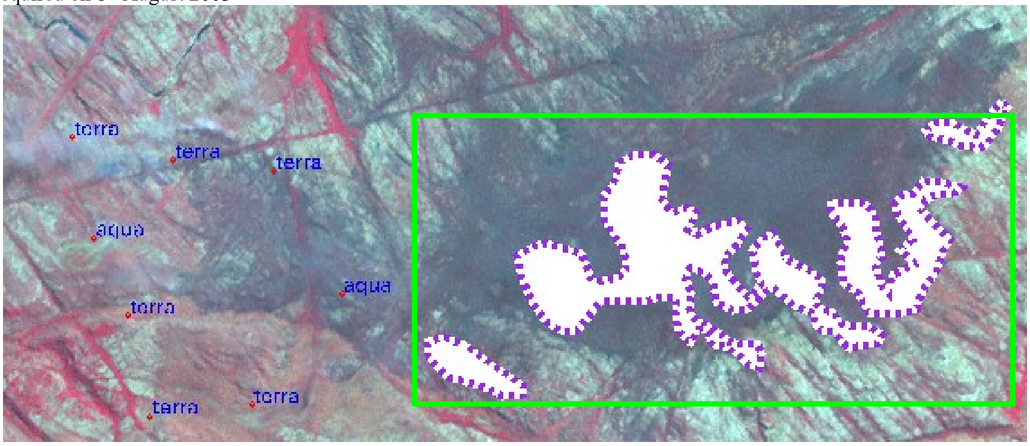
Undetected Mt Kembla 2007 bushfire was a typical example of Sentinel omission error that is attributed to fire spread rate and specific environmental conditions. This particular fire occurred at the under-story level burning rainforest species, and shrubs between the upper forest canopy and the ground. Because the dense canopies impeded circulation of heat from the surface and beyond under-story-canopy the temperature threshold for hotspot detection by the Sentinel system was not reached.



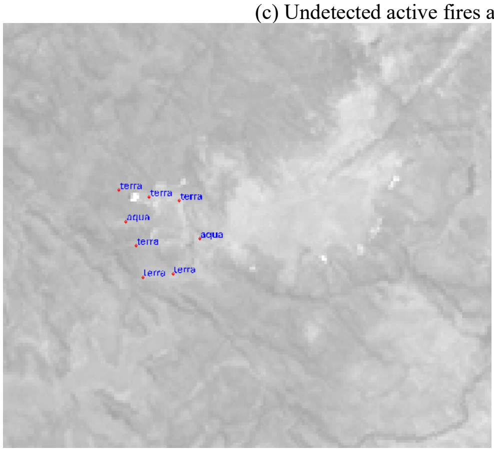
(a) Terra ASTER pass (composite product, bands 3, 2, 1) was acquired on 8th August 2003



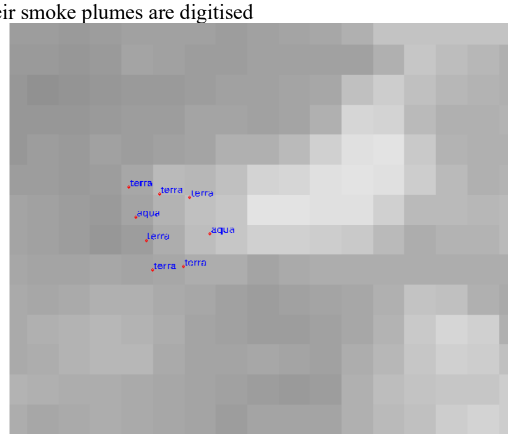
(b)Zoom area from previous map showing a few examples active fires on ASTER 15m which have not been detected by Sentinel



(c) Undetected active fires and their smoke plumes are digitised



(d) Terra ASTER image, thermal band 14 (10.95 - 11.65 µm) 90 m pixels acquired on 8th August 2003. This indicates the fire front as a series of bright spots



(e) Terra MODIS image, thermal band 31 (10.78 - 11.28 µm) 1000 m pixels acquired on 8th August 2003

Figure 5: Examples of omission and commission errors of AVHRR and MODIS hotspots using ASTER imagery. Note: the hotspots (red dots) shown are not to scale

Also dense smoke associated with cool air temperatures and a very slow dispersion rate could have hampered the detection of the fire by MODIS. AVHRR hotspots products tend to overestimate the number of hotspots in comparison with MODIS hotspots. Error assessment based on visual interpretation of imagery concluded overall commission errors of MODIS and AVHRR hotspots over the 5% sampling strata (regions) are 15% and 68% respectively, and overall omission errors of

MODIS and AVHRR hotspots are 17% and 23% respectively. A high commission error of AVHRR is due to high threshold values designed at continental application. The poor performance of the AVHRR algorithms (in terms of commission errors) is due not only to their quality but also to cloud cover, low satellite overpass frequency and the saturation of AVHRR channel 3 at about 321 Kelvin. Improvement in national fire detection probably can be achieved by further validation with a more extensive in situ dataset that expands at least three years of data over the whole of the Australian continent. An improvement may be considered to include the addition of adaptive contextual thresholds and an atmospheric correction for thermal bands. The geographic latitude ranges influence fire characteristics. We used three strata based on regions (latitude) including region 1 (10°S, 20°S), region 2 (20°S, 30°S) and region 3 (30°S, 43°S). Minimum and maximum temperature thresholds based on region is reported in Table 2 and is presented in Figure 6. Threshold values encompass a range of high temperature areas. Minimum temperature threshold values are consistent over the three regions on MODIS hotspots, and there is a linear but steady decrease for AVHRR from region 1 to region 3. However, maximum temperature threshold values remain the same over the three regions on AVHRR hotspots. This implies the need to re-assess threshold values used in the contextual AVHRR hotspot detection algorithm based on geographic areas.

Table 2: Summary of temperature threshold values for both MODIS and AVHRR hotspots over the 5% sampling three regions

Sensor	**Min temperature (K) based on region**			**Max temperature (K) based on region**		
	10°S - 20°S	**20°S - 30°S**	**30°S - 43°S**	**10°S - 20°S**	**20°S - 30°S**	**30°S - 43°S**
MODIS	305.1° K	305.1° K	305.1° K	451.8° K	500° K	500° K
AVHRR	296.2° K	292.8° K	288.3° K	338.4°	338.4° K	338.4° K

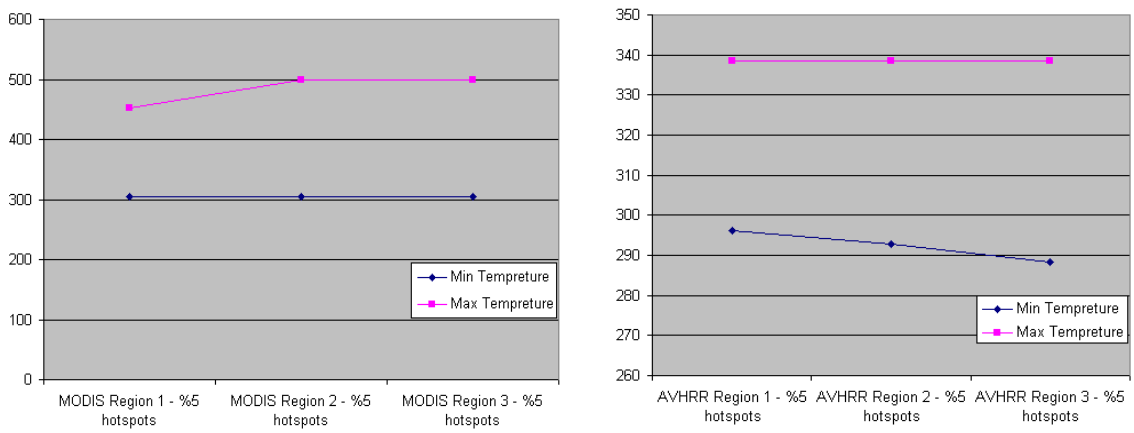


Figure 6: Overall performance of threshold values over three sample regions

A comparison of the Sentinel MODIS hotspot product (version C4) with coincident MCD45ML hotspot product (version C5) provided by University of Maryland (UM) revealed that although some fires did not appear in the C5 product compared to C4, but there was a global increase in the number of fire pixels up to 3%. Changes in version C5 of the code include the following (Giglio, 2009):

1. Rectifying a bug regarding switching between bands 21 and 22; band 21 was sometimes incorrectly used instead of band 22. This improved the number of fire pixels to the order of up to 2 percent.
2. Change in calculation of fire confidence because confidence of many fire pixels was significantly high in C4.
3. Change in calculation of fire radiative power (FRP).

Version C5 removed false alarms detected near to large fires; these false alarms would occur near true fires, but offset by about 10 km. This is introduced by a crosstalk-induced artifact caused by MODIS detector's anomaly in band 21. However, the rate of false alarms increased; this issue was addressed in version C6 at UMD.

4. Conclusions and Recommendations

In this study, it was established that multi-source earth observation data can play a useful role in validation of real and false fires. Key conclusions from the validation are:

- A method for assessing the accuracy of MODIS and AVHRR hotspot products has been developed. Li et al., (2000) established that about 4% of the fires detected are probably false alarms, but this study found that false alarms of MODIS and NOAA are 15% and 68% respectively. In addition, MODIS and NOAA respectively detected 83% and 77% of fires equal or greater than one km^2. The accuracy of MODIS data is considered to be superior to AVHRR data when detecting hotspots because it has higher sensitivity and fewer temperature saturation problems.
- The validation activities have resulted in the development of an error assessment database for future use once the hotspots algorithms are modified and updated. Also, hotspot fire detection accuracy assessment assists users to determine the quality of individual hotspot fire product. Access to a large archive of earth observation imagery has allowed maximising use of datasets for validation of hotspots products and can serve as an example for growing the use of Geoscience Australia earth observation archive into the future.
- Comparing the Sentinel MODIS hotspots (version C4) with coincident MCD45ML hotspot product (version C5 – subsequently reprocessed data) highlighted that some fires did not appear in the C5 product compared to C4, there was a global increase in the number of fire pixels up to 3%. In general, the difference is small (only a few percent) and insignificant for Australia. The Aqua MODIS shows the exact same trend. Sentinel has used the C5 algorithm since April 2008.

Key recommendations from the validation are:

- An upgrade to Sentinel's hotspot detection software in order to generate the Collection 6 (version C6) hotspot product is suggested. The upgrade will improve hotspots product quality offered from GA. The upgrade will make GA hotspot product more consistent with global historical hotspots archive.
- That a database of anthropogenic heat sources (e.g. plants, factories, etc) be maintained to enhance Sentinel spatial accuracy by attempting to filter out the false hotspots (man-made error sources) from real, active hotspots.
- The revision of AVHRR thresholds; it was demonstrated that hotspots products derived from NOAA tend to overestimate the number of hotspots in comparison to MODIS hotspots. Cross validation of AVHRR and MODIS hotspots over 5% of the target areas within the three regions highlighted that errors are linearly increasing from Region 1 towards Region 3. The thresholds values used for AVHRR are too high and the contextual thresholds do not yield satisfactory results. The performances obtained with the AVHRR hotspot detection algorithm are preliminary and need further validation with a more extensive in situ datasets which spans expands at least two years of data. An improvement may be considered to include the addition of adaptive contextual thresholds, and possibly an atmospheric correction for thermal bands.
- Further validation activities on an ongoing basis over the whole of the Australian continent. Also future studies should compare and validate various fire detection algorithms over local fuels and weather regimes for Australian landscapes (Forghani *et al.,* 2007a and 2007b, and *et al.,* 2014).

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