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ADVANCES IN THE REMOTE SENSING OF ACTIVE FIRES: A REVIEW

Detection, mapping and monitoring v1.0

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Version	Release history	Date
1.0	Initial release of document	26/10/2017

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Publisher:
Bushfire and Natural Hazards CRC

October 2017

Citation: Jones S, Reinke K, Mitchell S, McConachie F and Holland C (2017) Remote sensing of active fires: a review – detection, mapping and monitoring v1.0. Melbourne: Bushfire and Natural Hazards CRC

Cover: Karin Reinke

Advances in the Remote Sensing of Active Fires: A Review

Detection, Mapping and Monitoring v1.0

Background and Scope

The increasing risk of wildfire resulting from climate change has demanded an increase in information to support mitigation, response and recovery activities by fire management agencies. Subsequently, there is a need for an ongoing review of currently available and on-the-horizon information and technology.

Fire has important national significance as Australia faces ongoing environmental issues including loss of biodiversity, increasing urbanisation into bushland environments and increasing risks of wildfire. Fire regimes are an integral part of the ecosystem processes of Australian forests and a prominent disturbance factor. It affects successional rates of ecosystems, species diversity, can increase habitat fragmentation and alter landscape functioning. At the same time, fire is an important tool in management for ecosystem health and is frequently used for fuel hazard reduction.

Remote sensing data can assist fire management at three stages relative to fire occurrence including (i) Before the fire (fuel hazard measures, time since last burn) to assist fire prevention or minimisation activities, (ii) During the fire (near real-time detection and location of active fire areas and (iii) After the fire (mapping and assessment of burned areas). Active fires can be detected using satellite data because fire fronts are very hot compared to the background landscape temperature, and emit large amounts of energy that can be potentially be observed by thermal sensors on board satellites or aeroplanes.

This report focuses on passive satellite (or space-borne) sensing systems and is designed to provide the theory of active fire detection, and place experimental systems in the context of this theory. It examines previous

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sensing systems, their limitations and current information usage by fire management agencies. Whilst experimental satellite programs do not guarantee prolonged availability of data, it is important to understand and review capabilities to future proof our domestic fire management agencies to be ready for new data sources and information suites.

Introduction

Active Fires

Fire has been observed having both beneficial and detrimental effects on the environment. In populated areas or degraded environments wildfire can have catastrophic impact. As such the ability to detect and monitor active fires (fires which are alight) at near real-time on a local, national and international scale is an asset (Lentile et al., 2006; San-Miguel-Ayanz & Ravail, 2005). The impact of any active fire is based on a complex combination of vegetation type, fuel load, moisture and climatic conditions, factors which can be monitored for with remote sensing technology. Through improving fire detection and monitoring there has been improvement in active fire tracking, a better application of resources and a greater ability to have appropriate emergency responses (Davies, Ilavajhala, Wong, & Justice, 2009; Lentile, et al., 2006).

A number of active fire characteristics have been identified within remote sensing and fire ecology literature. These include, but are not limited to, flame height, fire duration, rate of spread and energy output (Lentile, et al., 2006). The fire temperature, size of fire, in situ vegetation and soil moisture are also all important factors when assessing an active fire (Kant, Prasad, & Badarinath, 2000; Lentile, et al., 2006; San-Miguel-Ayanz & Ravail, 2005). These indicators can be summarised in remote sensing identification terms into four spectral signatures; increased radiation (heat and light), an increase of aerosols (smoke), solid residue (char & ash) and change in vegetation and signature response, the burn scar (Robinson, 1991).

Barducci (2002) proposed that fire detection and monitoring should be able to achieve the following four outcomes. First is the identification of a fire front. This encompasses identification of the active burning fire and a recorded time and location. This is essentially a binary assessment of a landscape. The thermal energy released through combustion increases pixel brightness above a normal land cover response which is then captured by the sensors as they pass overhead indicating the presence of an active fire (Dozier, 1981; Louis Giglio, Loboda, Roy, Quayle, & Justice, 2009; Kant, et al., 2000). The second is the ability to estimate the radiant energy of a fire which provides indications to fire severity and intensity. Interpreting the fire's thermal signature comes from recording the heat and energy emitted by the fire front in relation to the surrounding environment, any known fuel loads (Louis Giglio, et al., 2009; Lentile, et al., 2006).

The third is continued monitoring of the burned area in order to detect traces of latent fire as well as the presence of residual vegetation not entirely burned. There are variations between, and even within, wildfire burn areas. For example there is a high degree of thermal energy and speed between a smouldering burn and an actively burning fire front in a vegetation blaze (Dennison, Charoensiri, Roberts, Peterson, & Green, 2006). Often change between a low intensity smouldering fire and an active fire front can occur in a short space of time, making temporal revisit by a satellite and sensor an important part of the detection process. Wildfires are also more active in the day than at night which has implications for any near real-time assessments (Wooster, Xu, & Nightingale, 2012).

Finally there is the mapping of the burned area or burn scar. Changes in the spectral responses due to fire activity removing vegetation are dependent upon local conditions. The soil type, prior vegetation and seasonality can all impact on the sensor response for the active and post fire assessments (Randriambelo, Baldy, Bessafi, Petit, & Despinoy, 1998; Stolle, Dennis, Kurniwan, & Lambin, 2004; White, Ryan, Key, & Running, 1996). A burn scar response show where a fire has burnt existing fuel load and is therefore unlikely to reignite. At the finer spatial resolution it can be differentiated from pixels contain vegetation which has been missed in the fire front.

History of Detection and Mapping of Active Fires

The oldest method for fire detection and monitoring is the use of fire towers. Active during peak fire seasons these structures were often remote lookouts. Towers, which are still used in peak times, require substantial manpower and provided only directional based fire information. Spotter planes are also still used and provide real time fire monitoring however the expense and flying range limited the usefulness (Matthews et al., 2010). Earth mapping sensors such as Advanced Very High Resolution (AVHRR) began to be used for broad scale environmental projects such as vegetation condition mapping including the identification of thermal hotspots using a technique developed by Dozier (1981).

The successful identification of hot spots from a satellite platform led to further investigation into the potential for fire monitoring. Muirhead and Cracknell (1984) and Matson *et al*. (1987) were among the first to detect vegetation fires using data from the AVHRR and NOAA-N sensors respectively. The presence of fire smoke and clouds were limiting factors in the success of these initial projects as was mistaking wildfire detection for other phenomenon such as oil well burning but these errors have been minimised through the refinement of sensor technology and active fire processing algorithms (Dozier, 1981; Louis Giglio, et al., 2006; Lentile, et al., 2006).

Multispectral sensors have radiometric sensors which operate in set bands. AVHRR, MODIS and Landsat are all multispectral sensors. The suitability and flexibility in fire detection depends on the sensor bands and bandwidth. For example the active fire detection capability of the Landsat TM Multi Spectral sensor is able to identify the presence or absence of large fires with a high degree of success but has a course spatial resolution (Barducci, et al., 2002). In comparison the MODIS and AVHRR sensors have bands which have been effectively used for fire detection and monitoring at finer scales (Lentile, et al., 2006).

It was application of the AVHRR Infrared sensors on the NOAA-N platform which were used by Matson et. al. (1987) and Muirhead and Cracknell (1984) to first identify active fires. The most commonly utilised sensors obtain the clearest signals through the Mid IR and Thermal IR (Robinson, 1991). MODIS, ASTR and AVHHR all have well defined IR fire detection algorithms for the Mid and Thermal IR ranges (Louis Giglio, et al., 2009; Kant, et al., 2000; Lentile, et al., 2006; San-Miguel-Ayanz & Ravail, 2005). The sensitivity of the IR sensors is an important factor to consider as saturation of the sensors, particularly in the Near Infrared range, just as an active fire meeting the required amount of energy to register in a pixel. Both aspects can be problematic for detection (Kant, et al., 2000).

The first uses of sensor in fire analysis limited to mapping the area of fires, tracking vegetation recovery and other post event investigations. They required the use of pre and post fire data (White, et al., 1996). After the success of Muirhead and Cracknell with the AVHRR, other satellite sensors were identified and subsequently used for active fire detection and monitoring. These included Geostationary Operational Environmental Satellites (GOES), the Defense Meteorological Satellite Program Optical Linescan (DMSP-OLS), the Along Track Scanning Radiometer (ATSR), and the Tropical Rainfall Monitoring Mission (TRMM) Visible and Infrared Scanner (VIRS). Considerable efforts have made to utilise existing sensors especially those with bands in the Near and Thermal Infrared bands. The technological advances of the late 1990's saw several research groups develop and improve the techniques for active fire monitoring using the existing satellite sensors (Lentile, et al., 2006; Randriambelo, et al., 1998) but identification limitations remained because these platforms were designed primarily for metrological based studies not fire detection (Cochrane, 2013; Stolle, et al., 2004).

Recently sensors have been developed specifically for the purpose of near real-time fire detection and active fire monitoring (Cochrane, 2013). For example; in 2000 when Idaho and Montana experienced a number of severe wildfires as part of its response the United States Forestry Service (USFS) dedicated effort into the potential of real-time remote sensed fire detection and monitoring. With the Goddard Space Centre (NASA) and the University of Maryland, the USFS also researched the suitability of various existing satellite based sensors for returning real time, regularly updatable, fire detection and monitoring information (Davies, et al., 2009; Sohlberg, Descloitres, & Bobbe, 2001).

The Moderate Resolution Imaging Spectroradiometer (MODIS) was the first operational sensor purpose built for fire detection. Launched in 1999 it uses the Near and Thermal Infrared wavelengths for fire detection purposes. There are numerous active fire products and services available for the MODIS sensor, all of which are well known and standardised (Louis Giglio, et al., 2006; San-Miguel-Ayanz & Ravail, 2005). Other sensor systems currently operational and have fire detection include the Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER), INSAT imager and Hyperion. These sensors, like MODIS, have also been actively tested and compared for accuracy, data processing, revisit times and suitability across a wide variety of terrains and have been further developed through the mid 2000's (Dennison, et al., 2006; Stolle, et al., 2004). This has included testing sensors in combination which is proved to be successful at accurately identifying more active burns (Stolle, et al., 2004).

Remote Sensing Theory of Active Fires

Remote sensing of active fires relies on the natural phenomenon where all objects will emit electromagnetic radiation based on the temperature of the object and although there is no perfect emitter of this radiation, this can be approximated as the black body radiation for an object. The measure of how efficient an object will emit radiation is termed the emissivity of an object, with a value of one being a perfect emitter. So conversely, remote sensing systems have been developed to measure where in the electronic spectrum that detected radiation lies, which can then give an approximation of the temperature of an object. Figure 1 shows the approximate wavelength of peak emission from a body as a function of the body's temperature.

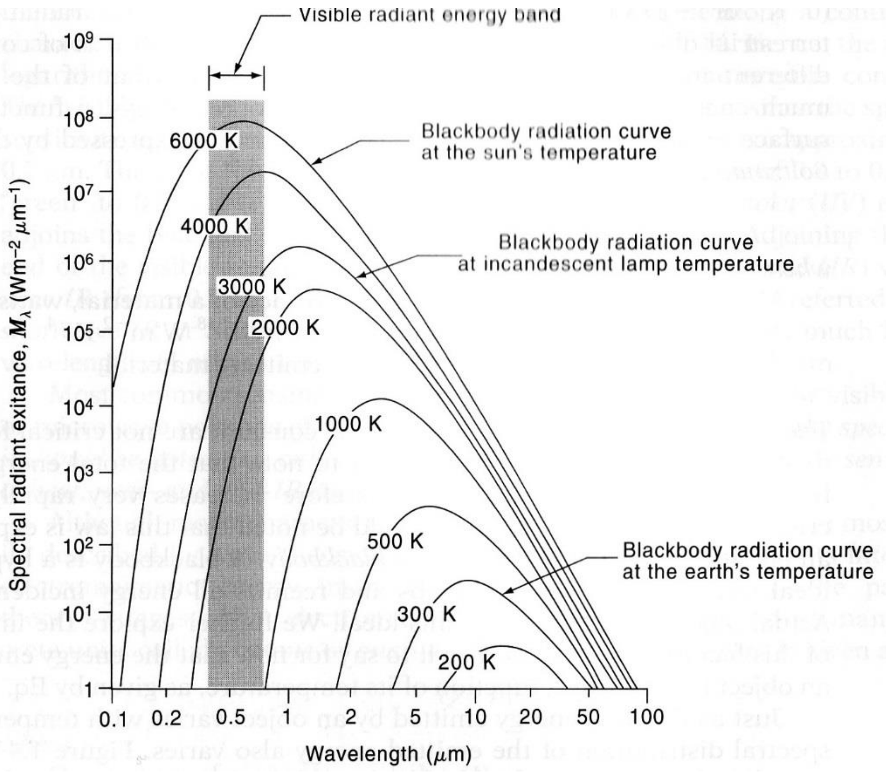


Figure 1 - Black body radiation curves for different temperatures (Lillesand et al., 2008).

The peak emission wavelength from the Sun at approximately 6000K (in reality it is 5778K) is at 0.5 µm, while the peak emission from the Earth at 300K (27°C) is at 10 µm and a fire at 800K will have a peak at 3.6 µm (Calle and Casanova, 2008). Generally, the temperature of a flaming fire can be anywhere between 800K and 1200K, and even as hot as 1800K. Smouldering fires will be much cooler and generally will be between 450K and 850K (Justice et al., 2006).

To detect an active fire by scanning over the entire range of wavelengths is not efficient or practical, so other techniques must be employed to discriminate fires from the background. These techniques include the use of multichannel detection over the wavelengths in the infrared range introduced by

Dozier (1981), where a comparison is made between the radiance detected at the wavelengths in the middle infrared (MIR) range, with those detected in the thermal infrared (TIR). The technique is based on the fact that under normal conditions, the background emission in the TIR range is significantly greater than that in the MIR range, but when a fire occurs, the emitted radiation becomes more intense at the shorter wavelength in the MIR range. This intensity difference can be seen in Figure 2, whereas the temperature increases, the radiance in the MIR range increases significantly when compared to the TIR range. This inversion in the intensities in the two regions is what satellite remote sensing exploits in detecting active fires (Calle and Casanova, 2008).

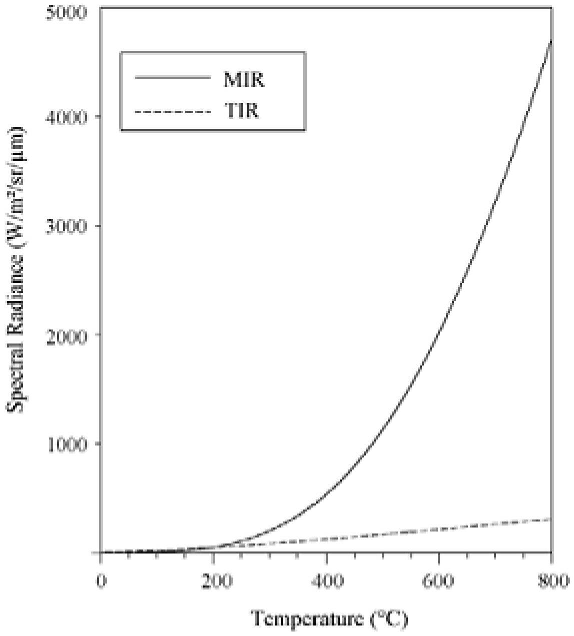


Figure 2 - Relationship between emitted spectral radiance and emitted temperature for the MIR and TIR spectral bands (Wooster and Roberts, 2007).

Figure 3 shows the relationship between the radiances detected for various objects and the respective wavelengths that demonstrate the inversion in detected emissions between the TIR wavelengths and the MIR wavelengths. This graph also illustrates the potential of the MIR wavelengths in detecting fires, with the high radiance values detected for fires compared with the low reflectance of the background giving a large contrast which can be exploited in the detection of hot spots (Zhukov et al., 2005a). In many cases, the contrast between the active fire and the background is what is important in determining if the target can be identified, rather than the intensity of the emitted energy (Robinson, 1991).

The intensity of the emitted energy from fires in the MIR region is much greater than that of the surrounding background that fires do not need to fill an entire pixel in order to be detected. Depending on the temperature of the fire and the pixel size of the sensing system, a fire occupying only as much as between 10^{-3} to 10^{-4} (or in other words, 0.1 to 0.01%) of the pixel can be detected (Lentile et al., 2006, Zhukov et al., 2006, Wooster and Roberts, 2007)

With the sensitivity at the sub-pixel level that is obtainable in the MIR range in detecting active fires allows for the use of satellite sensing systems with low to moderate spatial resolutions to identify relatively small sized fires. As sensor systems with these lower spatial resolutions are coupled with larger viewing swaths and higher temporal resolutions, the likelihood of detecting active fires increases, albeit at relatively larger extents (Zhukov et al., 2005b, Wooster and Roberts, 2007).

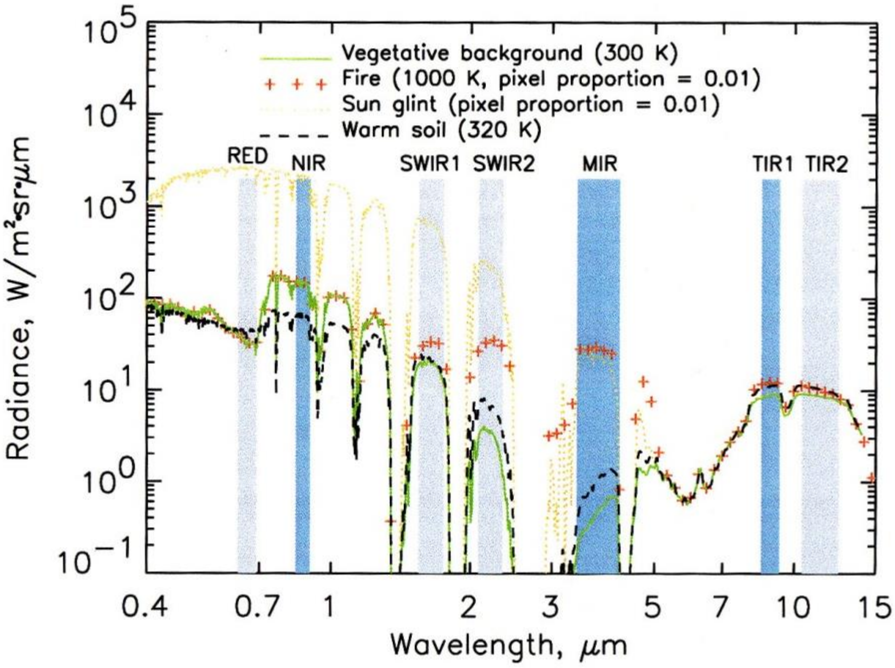


Figure 3 - Simulated top-of-atmosphere spectral radiance of a 1000 K fire against various typical backgrounds as a function of wavelength (Zhukov et al., 2005b).

The detected temperature of an object can also be related to the energy emitted by the object, with the relationship between the temperature detected and the emitted radiant energy being that the emitted energy is proportional to the 4th power of the temperature. This relationship is for the energy emitted per unit area, with a measure of the total energy emitted by, or the total power of, for example a fire, will need to take into account the area of the fire (Calle and Casanova, 2008).

A significant factor in the detection of active fires and the spectral bands that are used is in relation to the presence of cloud in the images, as they can limit the ability of the sensors in establishing the presence of fires, especially in the visual range. The majority of algorithms that are included in this review remove cloud covered areas imaged prior to running the detection algorithm. The smoke that is generated by fires though does not generally hinder the acquisition of data relating to the fires, as the smoke particles are commonly < 1µm, and the wavelengths used by the detection algorithms in the MIR and TIR ranges are appreciably larger than this value, thus limiting the influence of even thick smoke on the detection of active fires (Wooster and Roberts, 2007).

Fire Detection and Monitoring Algorithms

The satellite sensing systems that are currently in use, or have been used, in the detection of active fires use either one or a mixture of three algorithm types. These algorithm types are:-

1. Fixed Threshold
2. Contextual (relative/adaptive)
3. Multi Temporal

Fixed threshold algorithms are based on measuring the emitted energy for a pixel in either a single channel or over multiple channels and applying an empirical value, above or below which any pixel is defined as containing a fire. Fixed threshold algorithms are simple to apply and use, but do not scale well and are limited in use to local and regional scales and only to the particular season under study. Thresholds that have been developed and optimised for one location, such as woodland or savannah, and time, such as summer or dry/wet season, when applied to other operating environments can lead to significant errors of omission or commission, and as such are not suited for a global approach (Giglio et al., 1999, Ichoku et al., 2003, Oertel, 2005, Calle and Casanova, 2008, de Klerk, 2008, Giglio et al., 2008).

To overcome the limitations in using fixed threshold methods, modern active fire detection algorithms use contextual methods, which are also known as relative or adaptive algorithms. Contextual methods are based on detecting the difference in contrast between a hot pixel and the surrounding or neighbouring pixels. This is accomplished via statistical investigation of the background characteristics of the local pixels. These algorithms work much in the same way that the human eye will identify a fire visually by the contrast between a hot spot and the background. The relative nature of the algorithms means that contextual algorithms are more suited to the task of global fire detection in comparison to the fixed absolute threshold algorithms, by automatically adjusting the threshold levels for different regional and temporal conditions (Flasse and Ceccato, 1996, Oertel, 2005).

The final algorithm type available for active fire detection is the multi temporal method. The multi temporal method employs multiple passes of an area by a sensor system to detect changes in the radiance measured by that sensor in determining threshold levels for use in combination with the other examples of algorithm types. This method must also take into account temporal variability of the radiance values in the area, for example, differing illumination conditions. Although multi temporal algorithms are available for use for all sensor systems, they are more suited for use in systems which have a high temporal resolution, with images acquired at least once per day and are especially useful for geostationary satellite systems, which have the ability to capture images many times per hour (Oertel, 2005, Goessmann et al., 2009).

False Alarms

Taking readings only from the MIR and TIR wavelengths leaves the detectors at risk of raising false alarms, errors of commission that classify non-fire pixels as fire. False alarms can be generated when detecting with the MIR channel through warm surfaces, either sun heated ground or fire scars, or through intense solar reflection in the MIR channel from sun glint, often associated with clouds, water bodies and other specular reflectors.

The rejection of false alarms created by warm surfaces which have the same intensity over a full pixel as small fires at a sub pixel level in the TIR range, can be rejected by the use of ratios between the MIR values and the TIR values detected (Zhukov et al., 2005a). As previously mentioned and as shown in Figure 3, under normal conditions, the detected energy from warm soils in the TIR range will be higher than in the MIR range, so the ratio between the MIR and TIR will be smaller than for the case of a fire, where the MIR radiance will be much greater.

False alarms from sun glint are common when using the MIR and TIR channels individually to test for the differing contrast normally associated with fires. This is demonstrated in Figure 3, where the possibility of false alarms being generated in the MIR range from the radiance measures of reflected energy, from sun glint, are approximately equal to the radiance measures from fire. The simplest solution to this would be to only take measurements during the night, when no contamination from solar reflections will be present. This is not ideal, as fires are more likely to occur during the day and peak in the afternoon, with the corresponding emphasis on early detection requiring daytime measurements (Zhukov et al., 2005b, Wooster and Roberts, 2007).

To cater for these daytime reflectance issues, which are more prevalent at the shorter wavelengths, the algorithms must cancel out the effect from the reflected energy in the radiances detected in the MIR and TIR regions by taking measurements of the radiance values in the visible (VIS) and near infrared (NIR) portions of the spectrum, as these portions are dominated by reflected energy. As can be seen in Figure 3, the radiance values attributed to sun glint are an order of magnitude greater than the emitted energy. So a rejection test for false alarms will be dependent on whether there are returns registered in these bands, while a genuine fire will not produce any significant intensity in these bands (Calle and Casanova, 2008, Lentile et al., 2006).

Operational Earth Observing Systems for Active Fire Mapping

Remote sensing for the purpose of fire detection and monitoring has been well documented across numerous sensor systems over the last 30 years (Louis Giglio, Csiszar, & Justice, 2006; Kant, et al., 2000; Randriambelo, et al., 1998; White, et al., 1996). The techniques employed have improved identification of active fire locations, helped predict fuel loads and monitor post fire impacts on an environment (Lentile, et al., 2006). Sensors which cover the appropriate visual, NIR and TIR wavelengths have been utilised on both aerial and satellite platforms (Li, Vodacek, Kremens, Ononye, & Tang, 2005). A selection of commonly used earth observing systems for active fire are described in Table 1.

Table 1 – Selected satellite sensing systems relating to active fire detection using mid-points for wavelength bands. Adapted from (Fuller, 2000, Lentile et al., 2006). A complete table of expired, current and experimental earth observing systems may be found in Appendix 1.

Sensor System	Temporal Resolution	Spatial Resolution (m)	Swath Width (km)	VIS bands (µm)	MIR-TIR bands (µm)
ASTER	16 days	15 – 90	60	0.56, 0.66, 0.82, 1.65, 2.17, 2.21, 2.26, 2.33, 2.34	8.3, 8.65, 9.1, 10.6, 11.3
AVHRR	4 daily	1100	2400	0.63, 0.91, 1.61	3.74, 11.0, 12.0
Landsat 7 ETM+	16 days	30 - 60	185	0.48, 0.56, 0.66, 0.85, 1.65, 2.17	11.5
MODIS	4 daily	250 - 1000	2330	19 bands	16 bands (including 3.9, 11.0)
VIIRS	2 daily	375 – 750	3000	14 bands	7 bands (including 3.7, 8.5, 11.45

Satellite-based active fire products have been available since the 1980s, based on advanced very high resolution radiometer (AVHRR) sensors (Dozier 1981; Matson 1981; Matson & Holben 1987). Systems based on Moderate Resolution Imaging Spectroradiometer (MODIS) instruments have been available for over a decade, and these comprise the current most commonly used and well-developed active fire products (Csiszar *et al.* 2014).

Current active fire products are also available based on Along Track Scanning Radiometer (ATSR) or Geostationary Operational Environmental Satellite (GOES) sensors (Kasischke *et al.* 2003; Schroeder *et al.* 2008). Higher spatial resolution data such as from LANDSAT or ASTER sensors are more commonly used for validation purposes when testing other active fire products (Justice *et al.* 2002; Morisette *et al.* 2005). New products based on the Visible Infrared Imaging Radiometer Suite (VIIRS) are in development (Schroeder *et al.* 2014b).

AVHRR and MODIS are both moderate-resolution systems with approximately 1 km pixel size. Active fire products identify fires at this scale by classifying pixels based on thermal infrared signatures, as well as identifying smoke using visible and infrared bands (Hastings & Emergy n.d.). In Australia, AVHRR and MODIS data are incorporated in the Sentinel Hotspots and Landgate WA FireWatch monitoring systems.

AVHRR Active Fire Products

AVHRR sensors were originally designed primarily for meteorological monitoring, but additional applications were soon incorporated, including active fire monitoring. One advantage of AVHRR based active fire products has been a reasonable tradeoff between spatial and temporal coverage for global-scale fire monitoring. AVHRR provides daily coverage at a 1-km spatial resolution. Potential alternatives such as GOES or LANDSAT sensors less well suited to creating standard active fire products. GOES provides frequent sampling (up to every 15 minutes) but at a coarse spatial resolution (pixels of 4 km or larger), while LANDSAT provides finer detail with smaller geographic coverage and a longer revisit period of once every sixteen days (Li *et al.* 2000).

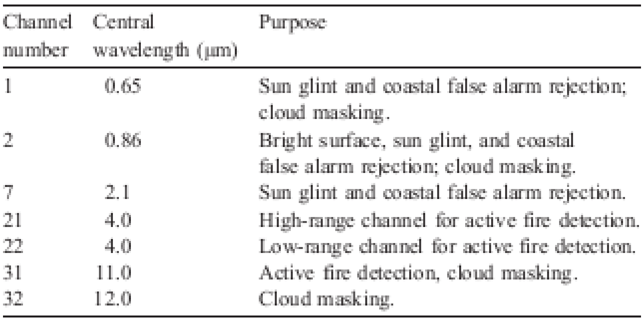
Additional advantages to AVHRR include a long history of monitoring, and that it is well-established with the characteristics of the sensor being widely understood (Li *et al.* 2000). AVHRR-based monitoring is used in large-scale and long-term fire monitoring (e.g., Stroppiana, Pinnock & Gregoire 2000), and in conjunction with other systems. It provides an archive of fire mapping going back to 1979 (Wooster *et al.* 2013). Validation based on higher quality fire mapping systems such as MODIS can improve the value of AVHRR data (Justice *et al.* 2011b).

MODIS Active Fire Products

The MODIS system, on-board the satellites Terra (morning) and Aqua (afternoon), provides two day and two night observations per day, Terra AM at 10:30 and 22:30 and Aqua PM at 13:30 and 01:30 (Justice et al., 2006), at a moderate spatial resolution of 250m, 500m and 1000m over a swath width of 2330km (Lillesand et al., 2008). It represented a significant advance on AVHRR fire monitoring, with spectral information more tailored to the purpose, however, limitations of the MODIS active fire products include missed detections of cool-burning fires, and some images generate a large number of unknown pixels. The temporal frequency may be insufficient to monitor rapidly changing fires (Creutzburg n.d.).

MODIS instruments provide data with a spatial resolution from 250 m to 1 km (Justice *et al.* 2011b). The system, with 36 spectral bands, is well placed to take advantage of the MWIR and TIR bands mentioned previously as necessary for fire detection. The principle bands that are used in the detection algorithm can be seen in Table 2.

Table 2 - MODIS channels used in the active fire detection algorithm (Giglio et al., 2003).



Channel number	Central wavelength (μm)	Purpose
1	0.65	Sun glint and coastal false alarm rejection; cloud masking.
2	0.86	Bright surface, sun glint, and coastal false alarm rejection; cloud masking.
7	2.1	Sun glint and coastal false alarm rejection.
21	4.0	High-range channel for active fire detection.
22	4.0	Low-range channel for active fire detection.
31	11.0	Active fire detection, cloud masking.
32	12.0	Cloud masking.

The outputs obtained from the MODIS system are organised and disseminated via products, a list of the fire associated products can be seen in Table 3, ranging from the Level 1 rapid response product generated from 2 to 4 hours after capture, up to the Level 3 composite products on either a daily or 8-day cycle. The Level 2 product MOD14 is the most basic product for wildfire (and other thermal anomalies) identification and is the basis for all other higher level products and covers an area of 2330km across track and 2030km along track and shows the detected fires for one image. The level 3 products are generated from the level 2 product and describe an area of one tile, or 10°x 10° at the equator, and contain a 1km grid showing the cumulative total of fires per grid either daily or over 8 days (Justice et al., 2002). Both the level 2 and level 3 products are normally generated approximately 7 days after the actual acquisition, which is a significant delay when taking into account the rapidly changing environment of wildfires. To overcome this, the Level 1 image data is released under a rapid response product, which is data directly from the data feed processed through the International MODIS/AIRS Processing Package (IMAPP) software, available at http://cimss.ssec.wisc.edu/~gumley/IMAPP/IMAPP.html, with the fire algorithm applied, and superimposed on the 250m corrected reflection product from the same feed (Justice et al., 2002).

Table 3 - Summary of MODIS fire products.

PRODUCT NAME	TERRA PRODUCT ID	AQUA PRODUCT ID
Rapid Response L1B	-	-
Thermal Anomalies/Fire L2 Swath 1km	MOD14	MOD14
Thermal Anomalies/Fire Daily L3 Global 1km	MOD14A1	MYD14A1
Thermal Anomalies/Fire 8-Day L3 Global 1km	MOD14A2	MYD14A2
Burned Area Monthly L3 Global 500m	MCD45A1	

Australian Fire Management Agency Use of Remote Sensing

A list of Australian fire management agencies was compiled, and information about agency roles and technology use was determined from information available online only, primarily from that agency's official website. Where satellite-derived fire data were mentioned they were obtained via one or more of three major sources:

- Geoscience Australia's Sentinel Hotspots;
- Landgate WA's FireWatch; and
- The North Australian Fire Information System (NAFI)

These systems include satellite data on current fires from MODIS and AVHRR. NAFI incorporates information from Landgate WA and Geoscience Australia but presents information more tailored to land managers in northern Australia

Table 4 summarises the role of major Australian fire management agencies in fire response, detection and post-fire activities, as well as identifying some of the technologies employed in fire detection and assessment. The roles and technologies investigated, as set out in Table , had a major focus on fire response, but with some prevention and preparedness, and post-fire activities covered. At a state level, rural fire services typically have primary responsibility for active fire management, with metropolitan fire services, parks and wildlife, and forestry agencies managing fire within their jurisdictions and providing support to other agencies when required. Additional organisations such as state emergency services usually have more of a supporting role, but may have more involvement during major fire emergencies.

Appendix 2 explains the agency abbreviations used and provides the website, and jurisdiction or location for each agency. Additional details about the roles and technologies explored can be found in Appendix 2.

Table 4. Roles and technology use of fire management agencies in Australia.

	RESPONSE																		PREVENTION AND PREPAREDNESS										POST-FIRE		
	Fire suppression			Detection and Assessment								External Data sources							Logistics	Threat Mitigation				Policy, Regulations, Land Use Planning		Research	Education and Awareness			Recovery activities	Fire Investigation	Post-fire or ongoing monitoring
	On ground	Aerial water bombing	Remote area firefighting	Field data, situation reporting	Fire towers, lookouts	Aerial observation, reconnaissance	Remote camera monitoring	Weather stations	GIS support, data manage., current	Risk Assessment	Modelling, fire behaviour analysis	Public	Bureau of Meteorology	FireWatch Australia	Lightning detection	Sentinel hotspots	Landgate FireWatch/Hotspots	North Australian Fire Information		Fire Management and Emergency	Hazard reduction, Ecological burns	Mapping	Fire Inspections, Risk Assessments	Development	Advice, Review		Community Education and	Incorporating indigenous knowledge	Warnings and alerts, public			
ACT Bushfire Council																									■							
ACT Rural Fire Service	■	■	■	■	■	■			■	■	■	■	■						■	■	■	■	■	■	■	■	■		■			
ACT Fire & Rescue	■									■		■	■						■	■	■		■	■	■		■		■		■	
ACT ESA: Risk									■	■	■								■	■		■			■							

ACT SES	■											■							■													
ACT Sust. Develop.																				■						■						
ACT Parks and Rec.	■		■			■			■		■								■	■	■					■	■			■		■
Fire and Rescue NSW	■			■		■			■	■		■	■						■	■	■		■	■	■	■	■		■	■	■	
Forestry Corp. NSW	■	■			■	■					■									■	■	■					■			■		
Nature Cons. Council																									■		■	■				
NSW Env. and Herit.	■	■	■	■	■	■			□	□	□		■						■	■	■	■	■	■	■	■	■		■	■		■
NSW Rural Fire Service	■	■	■	■	■	■		■	■	■	■	■	■	□					■	■	■	■	■		■	■	■	■	■	■	■	
NSW SES	■											■	■						■							■				■	■	
Land Resource Manage	■	■		■								■	■							■	■		■	■	■	■	■		■			■
NT Emergency Service	■			■						■		■	■						■						■				■			
NT Fire and Rescue	■	■	■	■						■		■	■							■	■		■			■	■		■			■
National Parks, Rec.	■			■					■				■					■		■	■	■	■				■		■			■
Emergency Man. Qld						■													■								■		■			
HQPlantations	■	■		■	■	■	■			■	■		■						■	■	■	■	■	■	■	■	■			■		■
Qld Fire and Rescue	■	■	■	■		■		■	■	■	■	■	■			■		■	■	■	■	■	■		■	■	■	■	■	■	■	
Natural Resources SA	■		■		■								■							■	■	■	■	■	■	■	■	■		■		■
Forestry SA	■				■															■	■											
Metropolitan Fire SA	■			■						■		■	■						■	■	■		■	■	■	■	■		■	■	■	
Natural Resources SA																				■	■	■		■						■		
SA Country Fire Service	■	■	■	■		■			■			■	■						■	■	■	■	■	■		■	■		■	■	■	
SAFECOM																			■				■	■			■			■		
Forestry Tasmania	■	■	■		■			■	■	■	■		■							■	■	■	■	■	■	■	■					■
Parks and Wildlife Tas	■	■							■	■	■		■							■	■	■	■	■	■	■						

State Fire Management																				■				■	■							
Tasmania Fire Service	■	■	■	■	■	■			■	■	■	■	■						■	■	■		■	■	■	■	■		■			
Tasmania SES										■									■								■		■			
CFA Victoria	■	■	■	■	■	■		■	■	■	■	■	■	□		■			■	■	■	■	■	■	■	■	■		■	■	■	■
DEPI	■	■	■	■	■	■		■	■	■	■	■	■	□		■				■	■	■	■	■	■	■	■		■	■	■	■
Fire Commisioner Vic																				■				■								
Melbourne Water	■	■		■	■	■							■		■					■	■	■								■		■
Metropolitan Fire Melb	■			■		■				■		■	■						■	■	■		■		■	■	■		■	■	■	
Parks Vic	■	■		■	■	■					■		■							■	■	■		■	■	■	■	■	■	■		■
Vic SES	■																		■								■		■	■		
Fire and Emerg. WA	■	■	■	■		■			■	■	■	■	■				■		■	■	■	■	■	■	■	■	■		■	■	■	
Parks and Wildlife WA	■	■		■	■	■		■	■	■			■			■	■		■	■	■	■	■	■	■	■	■	■	■	■		■
NAILSMA																										■		■				
Airservices Australia	■	■				■														■												
Attorney General																								■	■							
Aust. Defence Force	■																															
Fire and Emerg. Council																			■	■			■		■							
Bureau of Meteorology																						■				■	■		■			■
Bushfire CRC																							■			■	■					
Natural Hazards CRC										■	■									■		■	■		■	■	■					■
Risk Manag. Bushfires																				■			■		■	■						
CSIRO									■	■	■									■		■	■		■	■	■		■			■
Department of Justice																				■												

Fire Protection Assoc.																			■			■		■		■					
Geoscience Australia									■	■	■											■	■			■						■
Landgate									■		■											■	■			■						■
Aerial Firefighting		■	■			■			■										■		■					■						
Terramatrix																				■		■	■	■	■	■					■	

□ = planned or being researched, ■ = current. See Appendix XXX for full agency names and Appendix XXX for more detailed explanation of columns.

Experimental Satellite Sensing Systems for Active Fire Mapping

Although there are many examples of operational satellite sensing systems that are capable of mapping active fires, new experimental satellite sensing systems have been developed to counter limitations present in the current systems, such as the detection of small, low intensity fires. A comparison of the detection level for operational satellites versus that of BIRD can be seen in Figure 4. One such example is the satellites (current and planned) in Project FIREBIRD, which is a program operated by the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt - DLR). Project FIREBIRD came about from the experiences of operating the Bi-spectral Infrared Detector (BIRD) by the DLR in the years between 2001 and 2004.

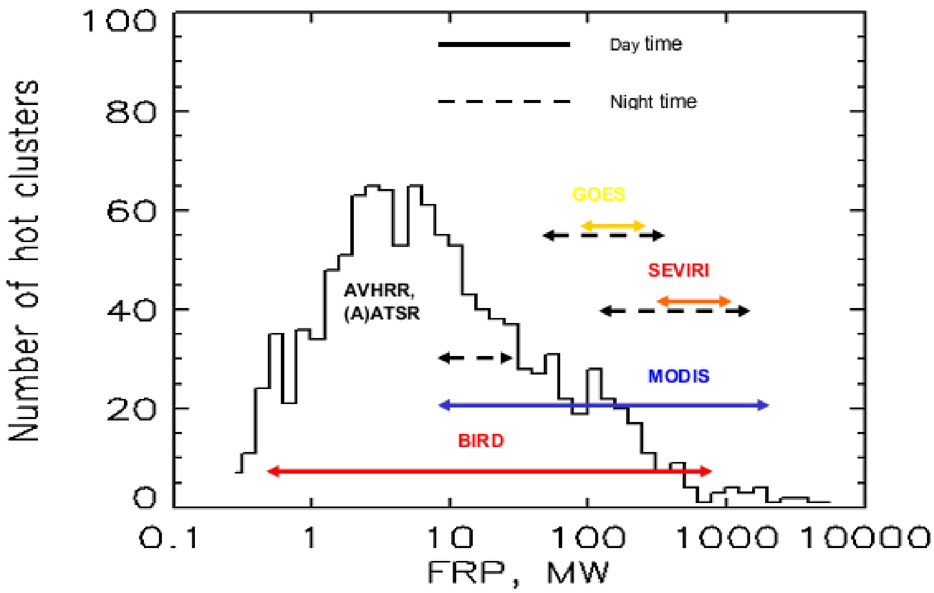


Figure 4 – Comparison of fire detection satellite sensing systems, with the range of detection shown in regards to Fire Radiant Power (FRP) (Oertel, 2007).

The BIRD satellite sensing system was developed to demonstrate the ability for a polar orbit satellite system with a spatial resolution to fill the gap present in detecting small, low temperature fires, i.e. fires at the beginning of their life. In experiments carried out by BIRD, a fire of 4m² was detected, while also possessing the ability to detect high intensity fires as well as improving the level of false alarm rejection (Zhukov et al., 2005a). This is an improvement over the level that can be detected by the current generation of fire detecting satellites, such as MODIS. For instance, Figure 5 shows a comparison of the output images and products of BIRD versus the same from MODIS of a fragment of the fires around Canberra on 26th January 2003. This image shows an increase in the number of small, low intensity fires (lower power output) as compared to MODIS, with the additional benefit of being able to distinguish fire front locations and directions of propagation.

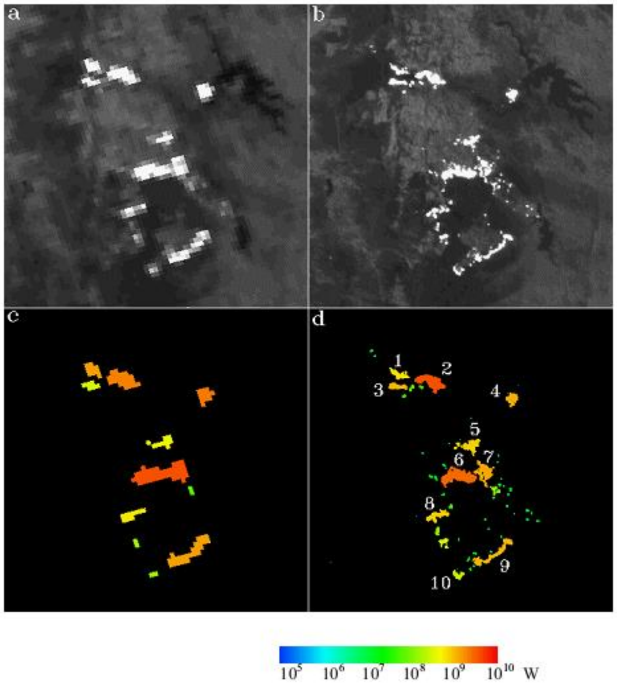


Figure 5 – Comparison between MODIS and BIRD images from Canberra, 26th January 2003. Image a) shows the MODIS channel 21 output, image b) showing BIRD MIR channel output, image c) showing the output from the MOD14 active fire product and d) showing the output of the BIRD detection and characterization product (Oertel et al., 2004).

The BIRD camera system also has similar advantages when compared to geosynchronous fire detection satellite systems, with Figure 6 showing a comparison of a fire in Brazil detected by both BIRD and GOES. This figure shows that while both systems detect the larger fire, only BIRD detects the numerous other lower power fires in the region.

The success of the BIRD satellite in detecting small, low temperature fires led to the creation of Project FIREBIRD, which is envisioned to launch and operate a constellation of small satellites based on the BIRD design. The first of these satellites is the TET-1 (Technologie-Erprobungs-Träger 1 - Technology Experiments Carrier-1) which was launched in July 2012 (DLR - Space, 2012). The TET-1 satellite is a technology demonstrator satellite, with the IR camera being one of eleven other experiments, with the IR camera system attaining exclusive use of the satellite 12 months after launch. The IR camera system on-board the TET-1 satellite is the same design as that for the BIRD satellite, and with the slightly changed orbital characteristics (500km versus 570km for BIRD) is expected to give improved performance to that of BIRD.

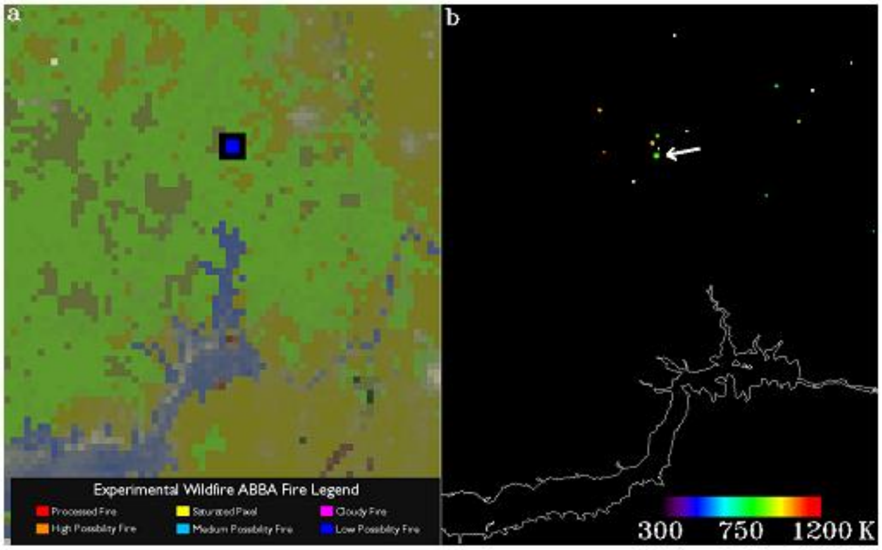


Figure 6 – Comparison of hot spot detection by a) GOES and b) BIRD; over Brazil on the 23rd November 2001 (Briess et al., 2003).

One disadvantage with operating polar orbiting satellites, especially at the low altitude that TET-1 is located in, is that the revisit time of each single satellite is approximately 3-4 days. Therefore, Project FIREBIRD is planned to launch a constellation of satellites based on the BIRD satellite. The next satellite, currently in construction, is the Berlin Infra-Red Optical System (BIROS), which is expected to be launched in late 2015. A further two satellites are to be funded and built in Mexico by the Agencia Espacial Mexicana (Mexico Space Agency – AEM), but with currently no firm date for possible launch.

The operation of polar orbiting satellites in a constellation has the effect of reducing the revisit time over a point on the Earth, and the more satellites in the constellation, the more significant the reduction in revisit time. For instance, as mentioned previously, TET-1 has a revisit time of approximately 3-4 days (depending on orbit and location on the ground), but with the addition of another three satellites to the constellation, the revisit time reduces to 6 hours. Adding even more satellites will continue to reduce the revisit time, with six satellites operating in a constellation reducing the time to 2 hours, which will allow for the rapid access to fire information (Eckhardt, 2010).

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APPENDIX 1 Tables of Sensors

Table 1: Proposed Sensors

Sensor System	Temporal Resolution	Spatial Resolution (m)	Swath Width (km)	VIS Bands µm	MIR – TIR Bands µm
SGLI	3 days	250 - 1000	1150	8 Bands	8 Bands
SLSTR	24 h (IR channels in cross-nadir swath 4 days (SW channels in dual viewing)	500 - 1000	1675	.555 .659	7 Bands
MSI	10 days, in daylight. More frequent possible for emergencies	10 - 60	290 (?)	7 Bands	6 Bands
AGRI		500 - 4000		10 Bands	.85 1.70 1.20 1.32
ABI (GOES-R)		500 - 2000		0.47 0.64	14 bands
AATSR	3 days (IR) 6 days (VIS)	10000 IFOV	500	0.555 0.659 0.865	
AHI		500 - 2000		3 Bands	13 Bands
IMAGER INSAT		1000 - 8000			

Table 2: Current or Experimental Sensors

Sensor System	Temporal Resolution	Spatial Resolution (m)	Swath Width km	VIS Bands µm	MIR – TIR Bands µm
TET-1/BIROS	Dependent on satellites in constellation (days to minutes)	42.4 - 357	179	.46 - .56 .56 - .72	3.4 - 4.2 8.5 – 9.3
HIMAWARI 8	10-30 minutes	500 - 2000	500	3 bands	13 bands
SEVIRI		1000 – 4800	9	0.56 to 0.71 0.74 to 0.88	9 Bands
VIIRS	twice/day (IR and day/night VIS/NIR channel) once/day (VIS)	375 - 750	3000	14 Bands	7 bands (including 3.7, 8.5, 11.45
WAOSS-B	5 days	185	533	0.6 to 0.67	0.84 to 0.9
OLS	twice/day in both VIS and TIR	500 – 560	3000	0.4 to 1.1 0.47 to 0.95	10.3 to 13.4
SPOT	1 day	1150	60-80	.5 - .59 .61 - .68	7.8 – 8.9 1.58-1.75
QuickBird	1–5 days	0.6 - 2.4	16.5 (at nadir)		
ATSR	3 Days	1000	500		
ATSR2	3 days (IR) 6 days (VIS)	1000	500		
ALI	16 Days	10 - 30	37		

ASTER	16 days	15 – 90	60	0.56, 0.66, 0.82, 1.65, 2.17, 2.21, 2.26, 2.33, 2.34	8.3, 8.65, 9.1, 10.6, 11.3
AVHRR3	12h (IR) 1 day (VIS)	1100 IFOV	2400	0.63, 0.91, 1.61	3.74, 11.0, 12.0
HSRA	24 hrs	372			
Hyperion	16 days	30 IFOV	7.5		
OSA	3 days	1 – 4	11	0.45 to 0.52 0.52 to 0.6 0.63 to 0.69	0.76 to 0.9
LISS-3	24 days, in daylight	23.5 -50	142	0.52-0.59 0.62-0.68	0.77-0.86 1.55-1.70
LISS-4	24 days, in daylight. 5 days for a target area	5.8	23.9 km Multispectral 70 km Panchromatic	0.52-0.59 0.62-0.68	0.77-0.86
ETM+ (Landsat 7)	16 days, in daylight.	15 – 60	185	0.48, 0.56, 0.66, 0.85, 1.65, 2.17	11.5
OLI (Landsat 8)	16 days, in daylight.	15 – 30	185	0.45 - 0.51, 0.52 - 0.60, 0.63 - 0.68	1.56 - 1.66, 2.10 - 2.30
TIRS (Landsat 8)	8 days	120	185		10.30 - 11.30 11.50 - 12.50
VIRS	Intertropical coverage: ~ 100-min intervals with longer gaps once or twice per day	2200	3000	22 Bands range 0.402-11.8	

MODIS	12 hours (long-wave channels) 1 day (short-wave channels)	250 – 1000	2330	19 Bands	16 Bands

Table 3: Sensors no longer in use

Sensor System	Temporal Resolution	Spatial Resolution (m)	Swath Width (km)	VIS Bands µm	MIR – TIR Bands µm
WAOSS-B	5 days	185	533	0.6 to 0.67	0.84 to 0.9
ATSR	3 Days	1000	512		1.6, 3.7, 11 12.0
ATSR2	3 days (IR) 6 days (VIS)	1000	512	0.55, 0.67	0.87, 1.6, 3.7, 11 12.0
AATSR	2-3 days (IR) 6 days (VIS)	1000 IFOV	512	0.56, 0.66, 0.86, 1.6	3.7, 11.0, 12.0
AVHRR	twice/day (IR) once/day (VIS)	1100 IFOV	2900	0.615, 0.912	3.74, 10.8, 11.0
AVHRR2	twice/day (IR) once/day (VIS)	1100 IFOV	2900	0.615, 0.912	3.74, 10.8, 12.0
HSRA	24 hours	372m			
LISS-1	24 days, in daylight	72m	148	0.49, 0.555, 0.65	0.815
LISS-2	24 days, in daylight	36m	74	0.45-0.52 0.52-0.59 0.62-0.68	0.77-0.86

Appendix 2 List of Australian fire management agencies

A list of Australian fire management agencies was compiled, primarily using a Google search. Search terms were generated by combining:

1. Place names , e.g., “Australia”, state names
2. Topic, usually “fire”, which also picks up “bushfire”, “wildfire”, “firefighting”, etc.
3. General terms , e.g., “management”, “response”, “agency”.

Sometimes more specialist terms expected to be used by management agencies were used as additional search terms such as “suppression”, “hazard reduction”, “detection”, “monitoring”, “mapping”, “aerial observation”, “logistics”, “research”. The language used on the websites of previously identified agencies was used to generate additional search terms.

In addition to Google searches, fire management agencies were identified using links and mentions on previously identified websites, as well as from Australian links on the Global Fire Monitoring Centre (GFMC) website at http://www.fire.uni-freiburg.de/links/australasia.html

The Australian fire management agencies included here do not represent a comprehensive list, but cover the major agencies involved in fire response at a national and state level. Agencies involved in areas such as research were less thoroughly investigated. The results were restricted to information easily available online. The lack of a listed role means it was not clear or explicit from the agency website, but doesn’t necessarily reflect a complete lack of involvement in this area.

Agency name	**Abbreviation used in Table**	**Location or Focus**	**Website**
ACT Bushfire Council		ACT	http://esa.act.gov.au/actrfs/learn-about-us/act-bushfire-council/
ACT Emergency Services Agency: Rural Fire Service	ACT Rural Fire Service	ACT	http://esa.act.gov.au/actrfs/
ACT Emergency Services Agency: Fire & Rescue	ACT Fire & Rescue	ACT	http://esa.act.gov.au/actfr/
ACT Emergency Services Agency: Emergency Management, Risk and Spatial Services Group	ACT ESA: Risk	ACT	http://esa.act.gov.au/emergency-management/
ACT Emergency Services Agency: ACT State Emergency Service	ACT SES	ACT	http://esa.act.gov.au/actses/
ACT Government Environment and Sustainable Development Directive	ACT Sust. Develop.	ACT	http://www.environment.act.gov.au/environment
ACT Parks and Recreation	ACT Parks and Rec.	ACT	http://www.tams.act.gov.au/parks-recreation
Fire and Rescue NSW	Fire and Rescue NSW	NSW	http://www.fire.nsw.gov.au/
Forestry Corporation of NSW	Forestry Corp. NSW	NSW	http://www.forestrycorporation.com.au/management/fire-management

Nature Conservation Council of NSW	Nature Cons. Council	NSW	http://nccnsw.org.au/programs/bushfire
NSW Office of Environment and Heritage (including Parks and Wildlife Service)	NSW Env. and Herit.	NSW	http://www.environment.nsw.gov.au/fire/
NSW Rural Fire Service	NSW Rural Fire Service	NSW	http://www.rfs.nsw.gov.au/
NSW State Emergency Service	NSW SES	NSW	http://www.ses.nsw.gov.au/
Department of Land Resource Management (including Bushfires NT and Bushfires Council)	Land Resource Manage	NT	http://www.lrm.nt.gov.au/bushfires
NT Emergency Service	NT Emergency Service	NT	http://www.pfes.nt.gov.au/Emergency-Service.aspx
NT Fire and Rescue Service	NT Fire and Rescue	NT	http://www.pfes.nt.gov.au/Fire-and-Rescue.aspx
Department of National Parks, Recreation, Sport and Racing (including Parks and Wildlife Service)	National Parks, Rec.	NT	http://www.nprsr.qld.gov.au/managing/fire_management.html
Emergency Management Queensland (including Queensland State Emergency Service)	Emergency Man. Qld	Qld	http://www.emergency.qld.gov.au/emq/
HQPlantations	HQPlantations	Qld	http://www.hqplantations.com.au/firemanagement.html
Queensland Fire and Rescue Service (including Rural Fire Service Queensland)	Qld Fire and Rescue	Qld	https://www.fire.qld.gov.au/
Department of Environment, Water and Natural Resources, SA	Natural Resources SA	SA	http://www.environment.sa.gov.au/firemanagement/home
Forestry SA	Forestry SA	SA	
Metropolitan Fire Service, South Australia	Metropolitan Fire SA	SA	http://www.samfs.sa.gov.au/site/home.jsp
Natural Resources SA Murray-Darling Basin	Natural Resources SA	SA	https://www.forestrysa.com.au/Fire
South Australian Country Fire Service	SA Country Fire Service	SA	http://www.cfs.sa.gov.au/
South Australian Fire and Emergency Services Commission	SAFECOM	SA	http://www.safecom.sa.gov.au/site/home.jsp
Forestry Tasmania	Forestry Tasmania	Tas	http://www.forestrytas.com.au/
Parks and Wildlife Service, Tasmania	Parks and Wildlife Tas	Tas	http://www.parks.tas.gov.au/
State Fire Management Council, Tasmanian Government	State Fire Management	Tas	
Tasmania Fire Service	Tasmania Fire Service	Tas	http://www.fire.tas.gov.au/
Tasmania State Emergency Service	Tasmania SES	Tas	http://www.ses.tas.gov.au/
Country Fire Authority of Victoria	CFA Victoria	Vic	http://www.cfa.vic.gov.au/
Department of Environment and Primary Industries	DEPI	Vic	http://www.depi.vic.gov.au/fire-and-emergencies

Fire Services Commisioner Victoria	Fire Commisioner Vic	Vic	http://www.firecommissioner.vic.gov.au/
Melbourne Water	Melbourne Water	Vic	http://www.melbournewater.com.au/whatwedo/supply-water/Water-catchments/Pages/Protecting-the-catchments.aspx
Metropolitan Fire Brigade Melbourne	Metropolitan Fire Melb	Vic	http://www.mfb.vic.gov.au/
Parks Victoria	Parks Vic	Vic	http://parkweb.vic.gov.au/learn/information-for-students/managing-our-parks/fire
Victoria State Emergency Service	Vic SES	Vic	http://www.ses.vic.gov.au/
Department of Fire and Emergency Services, WA	Fire and Emerg. WA	WA	http://www.dfes.wa.gov.au/alerts/Pages/default.aspx
Parks and Wildlife, WA Government	Parks and Wildlife WA	WA	http://www.dpaw.wa.gov.au/management/fire
Northern Australian Indigenous Land and Sea Management Alliance	NAILSMA	Northern Australia	http://www.nailsma.org.au/keywords/savanna-fire-management
Airservices Australia	Airservices Australia	National	http://www.airservicesaustralia.com/careers/aviation-rescue-fire-fighting/
Attorney General's Department (Emergency Management Australia division)	Attorney General	National	http://www.em.gov.au/Pages/default.aspx
Australian Defence Force	Aust. Defence Force	National	http://www.army.gov.au/Our-work/Community-engagement/Disaster-relief-at-home
Australasian Fire and Emergency Services Council	Fire and Emerg. Council	National and region	http://www.afac.com.au/
Bureau of Meteorology	Bureau of Meteorology	National	http://www.bom.gov.au/
Bushfire CRC	Bushfire CRC	National	http://www.bushfirecrc.com/
Bushfire and Natural Hazards CRC	Natural Hazards CRC	National	http://www.bnhcrc.com.au/home
Centre for Environmental Risk Management of Bushfires (University of Wollongong)	Risk Manag. Bushfires	National	http://smah.uow.edu.au/icb/cermb/index.html
Commonwealth Scientific and Industrial Research Organisation	CSIRO	National	http://www.csiro.au/
Department of Justice (Inspector-General for Emergency Management)	Department of Justice	National	http://www.justice.vic.gov.au/utility/contact+us/inspector-general+for+emergency+management.shtml
Fire Protection Assiciation, Australia	Fire Protection Assoc.	National	http://www.fpaa.com.au/
Geoscience Australia	Geoscience Australia	National	http://www.ga.gov.au/hazards/bushfire.html
Landgate: Fire Monitoring services	Landgate		https://www.landgate.wa.gov.au/corporate.nsf/web/Fire+Monitoring
National Aerial Firefighting Centre	Aerial Firefighting	National	http://www.nafc.org.au/portal/
Terramatrix	Terramatrix	National	http://www.terramatrix.com.au/

Appendix 3 List of fire management roles and technologies

Roles were identified from general webpages, with a particular focus on the “About us” or similar section, as well as specific fire management webpages for agencies with a broader scope. Within site searches were also used to look for relevant keywords. Where available, the agency’s most recent annual report was also checked. In some cases, additional details were gathered from an agency’s employment opportunities offered, other attached documents (e.g., reports, procedures, media releases), or official twitter, Facebook, or YouTube videos.

In some cases very little detail was available on an agency. It is assumed that larger agencies will have more comprehensive websites and the information collected reflects something about the relative importance of various agencies from a broader fire management perspective.

Agencies with a broader emergency management role, such as State Emergency Services often had website information about disasters in general which could not be separated from their role in fire management specifically. Common expected roles such as on-ground situation reporting could not always be determined because they are rarely stated explicitly on websites. In reality agencies do not operate in isolation and sharing of roles and data will occur, particularly among agencies in the same region. Data sharing arrangements are important to fire management but this information is not always easily available.

Additional Google searches were employed to check for specific areas that had not been identified using these other methods. These searches combined the following search terms:

1. Agency name
2. Name of specific role or technology, e.g., “Sentinel”, “GIS”, “fire tower”, “policy” etc

Roles and Technology	Notes
Fire suppression	Firefighting activities to control active, unplanned fires
On ground	Fire trucks and on-foot fire suppression activities
Aerial water bombing	Via helicopter or aeroplane
Remote area firefighting	Specialist teams for fire suppression in less accessible regions
Detection and assessment	Data on active fires obtained from within the agency
Field data and situtation reporting	Information from on-the-ground, e.g., first responder report
Fire towers, lookouts	Use of vantage points to detect or assess fires
Aerial obs, reconnaissance	Plane or helicopter observation platforms
Remote camera monitoring	Stills or video
Weather stations	Permanent or portable stations providing information on weather conditions

GIS support, data management, current maps	Spatial support services providing current, continuously updated data
Risk Assessment	Determining safety of managers and the community during an active fire
Modelling, fire behaviour analysis	Prediction of fire behaviour or best suppression approaches
External data sources	Data on active fires obtained from outside the agency
Public	Public information, e.g., 000 calls
Bureau of Meteorology	Weather, monitoring and modelling services
FireWatch Australia	Smoke detection sensor system. See http://www.firewatchaustralia.com/
Lightning detection	Sensor systems for detecting lightning strikes
Sentinel hotspots	Geoscience Australia fire detection system based on satellite systems MODIS, NOAA.
Landgate Firewatch/Hotspots	Landgate WA fire detection system based on satellite systems MODIS, NOAA, Landsat etc.
North Australian Fire Information	Complies information from Sentinel, Landgate Firewatch, etc. See http://www.firenorth.org.au/nafi2/
Logistics	E.g., coordination, communications support
Threat mitigation	Activities for reducing fire risk or managing fire regimes
Fire management and emergency planning	
Hazard reduction, ecological burns	"Burning off" and other planned burns. Additional clearing, fuel reduction, etc.
Mapping	Mapping for planning or threat mitigation purposes e.g., fire risk maps, evacuation routes
Fire inspection, risk assessments	E.g., development fire safety compliance checks. Determining risk before a fire event
Policy, Regulations, Land Use Planning	Broad-scale planning for fire mangement
Development	Major role in developing plans or policies
Advice/Review	Advisory or review role in plans or policies

Research	Research on any aspect of fire management
Education and Awareness	Working with the community or other managers
Community education and engagement	Teaching the general public about fire safety or management awareness
Incorporating indigenous knowledge	Formal programs to incorporate indigenous fire management
Warnings and alerts, public information	Providing information to the public on current fires and fire risk
Post-fire	Role after fires
Recovery activities	E.g., clean up activities after bushfire
Fire investigation	E.g., arson investigations, post-incident analysis
Post-fire or ongoing monitoring	E.g., monitor vegetation response to burning regime