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Active Fire Detection for Fire Emergency Management: Potential and Limitations for the Operational Use of Remote Sensing

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Abstract. The use of the mid-infrared and thermal bands of sensors on board airborne platforms and satellites permits the detection of active fires on the Earth's surface. This application has been available to the fire-fighting community for many years. However, limitations in the fire detection capabilities of the sensors and/or the lack of adequate re-visit frequency have prevented the use of these systems for operational forest fire-fighting. In addition to mobile systems, remote sensors positioned on fixed fire-watch towers have also been used for active fire detection. These instruments are often positioned in strategic look-out places to provide continuous monitoring of the surrounding areas. They locate fires through the detection of either hot spots (areas of increased temperature in comparison to the background) or smoke plumes produced by the fires. This article evaluates the use of existing remote sensing systems for active fire detection, with emphasis on the applicability of these systems for fire emergency management and fire-fighting. Long-range remote sensing devices on board satellites are considered, airborne systems are assessed, and short-range fire detection instruments on fixed ground platforms are reviewed. A short introduction to forthcoming satellite systems, which will be based on the combined use of several small satellites, is presented. The advantages and drawbacks of the different systems are evaluated from a fire management perspective.

Key words: active fire, early fire detection, remote sensing, satellite systems, infrared spectrum

1. Introduction

Fires were once a natural phenomenon that helped to shape species distribution, contributed to the persistence of fire-dependent species, and assisted the natural evolution of ecosystems. Nowadays, however, in many areas of the world fires are the result of increasing human pressure on the environment; in Europe, for example, only 5% of forest fires are of natural

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causes. Often these fires cause irreversible damage to fragile natural ecosystems and human assets. Fires are also a source of emissions into the atmosphere, and cause the loss of extensive carbon sinks in tropical and boreal forests. Although the impact of fires around the world is large, the available information on fires and their effects at the global or regional scales are still very limited.

The need for early fire detection varies according to numerous factors. Fires constitute a threat when they occur on either fairly populated regions or areas of high environmental value. However, not all forest fires cause environmental damage. Hence, the urgency for fire detection and fire-fighting changes according to the nature of the fire. For instance, natural fires, which may be considered a vital alteration of an ecosystem, do not need to be extinguished. They are only extinguished when they are considered a threat to human assets. Human-caused fires, on the other hand, are often extinguished as soon as possible. Early detection of these fires is clearly aimed at fire-fighting. Therefore, it is assumed that early detection is only needed when resources for fire-fighting or fire control are available. An analysis of the requirements of the fire suppression community for early fire detection in Europe resulted in a maximum detection time of 15 min from the start of the fire (INSA, 2000). This analysis showed that the value of the information on fire detection decreases according to a negative exponential curve. This rapid loss of value of fire detection information can be easily explained. Fires are usually easy to extinguish in an early stage; once a fire has reached a fairly large size, operations for fire-fighting become very complicated and the control of the fire depends largely on the meteorological conditions that determine fire spread. In sparsely populated areas, where fires are not extinguished, fire detection is only needed for monitoring the environmental impact. Early detection is thus not necessary.

In Section 2 of this article, a review of existing methods for remote detection of forest fires is presented, including a multi-stage analysis of remote sensing of active fires. Ground detection systems (fairly close to the fire location) are analyzed in Section 3. Next, airborne and satellite remote systems are described, in Sections 4 and 5, respectively. This article differs in its focus from previous reviews of remote sensing of forest fires. It is not the intention of the authors to describe all of the existing remote sensing systems used for fire detection, but to highlight those that can contribute significantly to fire emergency management. It should be noted at this stage that most of the satellite systems routinely used for fire detection were not designed for this application and have never been used by the operational forest fire community. In a very few cases, satellite systems have been coupled with other airborne or ground devices for improved fire detection (Kelha *et al.*, 2001).

2. Methods for Remote Sensing of Fires

Fire detection by remote sensing systems is usually based on:

- Detection of hot-temperatures above normal environmental temperatures (single or multiple threshold methods).
- Detection of hot-temperatures with respect to the background (contextual methods).
- Detection of smoke plumes produced by fire emissions.

2.1 DETECTION OF HOT-TEMPERATURES ABOVE NORMAL ENVIRONMENTAL TEMPERATURES (SINGLE OR MULTIPLE THRESHOLD METHODS)

Fire produces a local elevation of the temperature (hot spot) above the normal environmental temperature, which may be detected by a remote sensor. All the hot spots detected by the system are then identified as fires.

Several bands in the electromagnetic spectrum provide a differentiation between a hot-spot (fire) and the surrounding cold background. Commonly, mid-infrared and thermal bands are used for this purpose. The strong signal of fires in the mid-infrared wavelengths makes this the most suitable part of the spectrum for their detection. Figure 1 (Kennedy *et al.*, 1994) shows the radiation emitted in the different bands of the electromagnetic spectrum by fires burning at several temperatures. Common temperatures observed in wildland fires (typical temperature of 800 K for burning grass) produce a

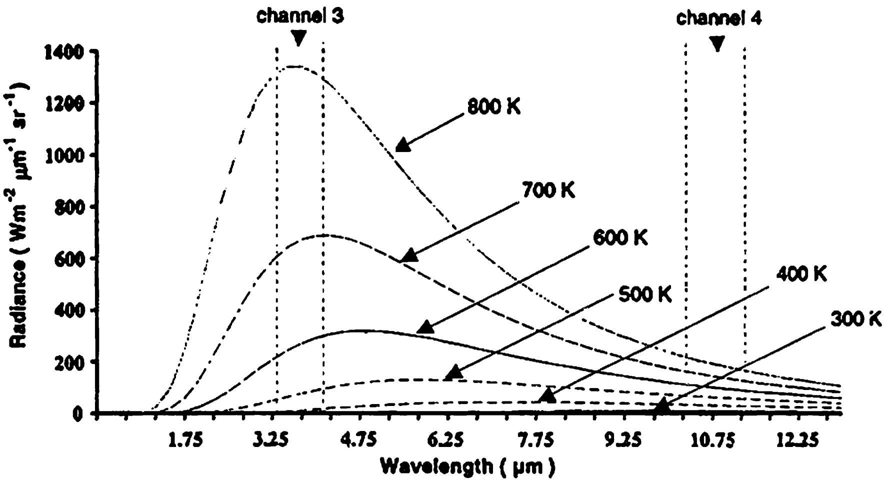

Figure 1. Radiation emitted in the different bands of the electromagnetic spectrum by fires of several burning temperatures.

peak radiation between 3 and 5 μm. This mid-infrared spectral window is suitable for fire detection because it is far from the peak of the Earth and Solar radiations at 0.5 and 9.7 μm, respectively. Fires also radiate in the thermal part of the spectrum, i.e. between 8 and 12 μm; however, the peak radiation at these wavelengths corresponds to a normal environmental temperature of 300 K. For instance, a burning grass fire, which has its peak emission at the mid-infrared window, would be hardly detectable by thermal channels (8 and 12 μm), as shown in Figure 1. Robinson (1991) provided a detailed description on the optimality of each spectrum window for fire detection. Additionally, a comprehensive description of thresholding algorithms and their application can be found in Arino *et al.* (1993) and Arino and Melinotte (1995). However, the main limitation to the detection of active fires from satellite sensors is still the saturation of the mid-infrared channels at fairly low temperatures (e.g. 325 K for the NOAA AVHRR sensor).

Fire detection by remote sensing systems depends not only on the burning temperature, but also on the size of the fire. The higher the fire temperature, the smaller the fire size needed for its detection. Algorithms that use a fixed environmental temperature threshold work well when calibrated for standard local conditions. For an optimal performance of the detection systems it is required that average environmental temperatures fall below fire temperature. This often happens in high latitude areas. These systems are not reliable in Mediterranean latitudes, however, where there are sparsely vegetated areas which can easily reach high enough temperatures in summer time to saturate the sensor channels. Accordingly, these algorithms produce a large rate of false alarms on these areas. One example of these fixed threshold algorithms is that proposed by Kaufman *et al.* (1990) for NOAA AVHRR satellite sensor data. According to this algorithm and area was classified as a fire when it met a set of constraints:

T3 (Temperature measured in the Mid-Infrared channel) $\geq$ 320 K

T3 $\geq$ T4 (Temperature measured in the Thermal channel 4) $+$ 10 K

T4 $>$ 250 K

When using satellite imagery, a possible solution to minimize the rate of false alarms is the utilisation of night-pass images, in which average environmental temperatures are low (Langaas, 1993). The main drawbacks of using night-time imagery are firstly, that the algorithms tend to miss some of the fires because of the reduced fire intensity at night, and secondly, that they do not detect small fires, which ignite during the day and are extinguished the same day. For instance, in Europe, the highest fire occurrence is between 12:00 and 14:00 h (European Commission, 1996).

2.2 DETECTION OF HOT-TEMPERATURES WITH RESPECT TO THE BACKGROUND (CONTEXTUAL METHODS)

In the previous approach all the hot spots that had an above-average temperature were considered as fires. This produced a series of false alarms in areas that were overheated during summer time. Flasse and Ceccato (1996) proposed a contextual algorithm to eliminate these false alarms. According to this algorithm a hot-spot is considered a fire only if its temperature is above the temperature of its surrounding areas. The algorithm identified potential fire areas which satisfied the following criteria:

$$T_3 \text{ (Temperature measured in the Mid-Infrared channel)} \geq 311 \text{ K}$$

and

$$T_3 - T_4 \text{ (Temperature measured in the Thermal channel 4)} > 8 \text{ K}$$

Next each potential fire (PF) was confirmed as a real fire when it was different enough from its background, i.e. satisfied the following criteria:

$$T_{3PF} - [T_{3b} + 2\sigma_{3b}] > 3 \text{ K}$$

and

$$T_{34PF} > T_{34b} + 2\sigma_{T34b}$$

Where PF refers to potential fire temperatures; T_{34PF} is the difference (T_3–T_4) of the potential fire area; T_{3b} and σ_{3b} are the temperature and its standard deviation of the background in channel 3; and T_{34b} and σ_{T34b} are the mean and standard deviation of the difference (T_3–T_4) in the background areas.

This algorithm eliminates false alarms due to the identification of hot spots as fires. However, false alarms are also found with the detection of fires along water lines. Along these lines the ground areas are always hotter than the surrounding background temperature, which includes water pixels. A solution to this problem is to divide the background surrounding the hot-spot in four quarters. The hot spot is then considered a fire only if it is hotter than each of the four separate backgrounds. Problems can also arise when not enough background for comparison can be found. This is due to the saturation of the system channel in an extensive area of high temperatures. Ravail and San-Miguel-Ayanz (2002) evaluated the performance of Flasse and Ceccato's contextual algorithm in Spain in 1997 and 1998 on Advanced Very High Resolution Radiometer (AVHRR) images. They found that over 90% of the detected fires were false alarms. These false alarms were caused by the above-mentioned problems of overheating in large areas of Central Spain, and by the systematic error on land-water interfaces. The fire detection accuracy increased as the size of the fire grew.

In addition to false fire detection due to ground overheating, one of the main sources of false alarms common to the above fire detection algorithms is the presence of clouds. When illuminated by sunlight, clouds typically appear as regions of elevated mid-infrared values and reduced temperature. The net increase in the difference between mid-infrared and thermal channels makes clouds resemble fires and induce system false detections (Giglio *et al.,* 1999). In the case of using satellite imagery, the scan-angle for the image acquisition can also influence fire detection in the thermal infrared spectrum (Boles and Verbyla, 1999). A large number of false alarms is produced when the scan angle is small, i.e. the image is acquired far from the nadir (perpendicular to the ground at the observation point) position.

2.3. DETECTION OF SMOKE PLUMES PRODUCED BY FIRE EMISSIONS

Fires produce emissions into the atmosphere in the form of a column of smoke, referred to as smoke plume. Image processing algorithms can be used to single out this smoke plume in contrast to its background, and associate it to a fire. Although these systems eliminate false alarms produced by overheating of ground areas, they also present some limitations. The limitations arise from two facts; first, the smoke plume can only be detectable some time after the fire has started; and second, smoke is often conducted along the surface and emerges in an area different from that where the fire started. False alarms can also arise from the confusion with clouds. The application of smoke plume detection, which is available for some of the fire detection systems from satellite imagery, is presented in Section 5 of this article.

The methods for smoke plume detection are often used for monitoring the smoke spread coming from extreme fire events such as the fires in Southeast Asia in 1997, Central America in 1998, or Australia in 2002. These extreme fire events cause health problems to the human settlements in large areas around the fire location. Also, given the large size of the smoke plumes, these can travel long distances, maintaining their damaging effects to affect faraway locations.

Often, fire or smoke detection algorithms are coupled with other algorithms to eliminate false alarms. The systems for early fire detection are further linked to a GPS or another geo-positioning system, a geographic information system in which other ancillary information and current meteorological data are stored, and often to an expert system that can provide rule-based decisions for accessing or extinguishing the fire. A complete system is linked through safe telecommunication channels, including sound and image transmission devices, e.g. the DEDICS described in Wybo *et al.* (1998).

3. Ground Systems

Ground systems are often situated in look-out points from which it is possible to survey a fairly large area. The most common mechanism for fire detection on these points is human surveillance. The only drawback of this mechanism is the demotivation of the personnel. Human surveillance is slowly being replaced by automatic surveillance by means of fire and/or smoke detecting systems that provide the exact location of the fire spot. In some cases, the detection devices are coupled with video systems that permit real-time observation of the terrain, which helps eliminating false alarms.

Ground automatic detection systems can make use of cameras mounted in towers, buildings or masts with good visibility of the surveyed terrain. The cameras can be fixed (attached to the structure) or mounted on a positioning system to vary the azimuth and elevation angles. When using fixed cameras, several cameras are needed to survey the surrounding area, the number of units depending on the optical system used. Alternatively, a positioning system can be used to survey the entire environment by varying automatically the scanning angles. The detection delay depends on the scan velocity given by the motors and the optical system in the camera. It should also be noted that the image processing requirements for automatic detection are higher when using mobile sensors. The sensor technologies used in today's automatic ground detection systems are mainly infrared cameras and visual cameras.

Autonomous detection of hot spots in the infrared part of the electromagnetic spectrum is the basis for several commercial systems, such as BOSQUE (IZAR-FABA) and BSDS (Teletron). Fires can be detected day and night and the required image processing is simpler than in the autonomous detection using visual cameras. Most infrared ground systems use infrared cameras with detectors in the mid-infrared band because of its low atmospheric attenuation; this permits detection of forest fires at large distances. High resolution infrared cameras have been shown able to detect small fires (about 1 m^2) several km (i.e. 10–20) away.

Image processing in infrared detection systems is typically based on the assumption that the fire gives rise to the highest infrared radiation intensity. Threshold-based criteria are used for fire segmentation from the background. The computation of the threshold values is highly application-dependent and many techniques can be used for this purpose. However, basic infrared detection systems provide false alarms due to the large number of objects that produce significant radiation in the infrared bands. The most common sources of false alarms are solar effects, heated objects, artificial lights and combustion sources due to human activities. The average mid-infrared intensity of heated objects, such as engines and chimneys, is not high when compared to the one produced by fires. This allows filtering of false alarms coming from these objects, using adaptive threshold techniques. However, solar reflections in rocks, stones, roofs, roads, and metallic structures can generate responses in infrared images similar in intensity to the ones produced by fires and therefore thresholding can not be applied satisfactorily.

Furthermore, false alarms due to artificial lights and combustion sources that do not correspond to forest fires (e.g. fires in camping areas, agricultural burnings and rubbish dumps) can cause significant high-intensity regions on infrared images. In these cases, other information sources should be applied. In Arrue *et al.* (2000) an intelligent system for fire alarm reduction is presented. This system uses correlation techniques and neural networks to eliminate high intensity false alarm spots based on the detection of the flame oscillations in the infrared response (Ollero *et al.,* 1999). Furthermore, it includes geographic information and forest fire detection expert-rules to discriminate automatically between fires and false alarms. Some of these techniques have been integrated in the BOSQUE and the DEDICS systems.

Autonomous detection by means of visual cameras is used by commercial systems such as the ARTIST FIRE, developed by T2M. These systems are based on smoke plume detection in the visible part of the electro-magnetic spectrum. Both black and white and colour cameras have been used in visual automatic fire detection systems. When using black and white cameras, the detection is based on temporal contrast differences with the natural background. The black and white images are divided in certain areas according to the distance to the camera. These areas are analysed in time-series of images, and the regions that change in this time-series are considered as smoke plumes. Although the system is useful for nearby smoke plumes detection, it fails when considering distant fires. Most smoke segmentation methods aim at discriminating smoke from other objects with similar visual characteristics. Some methods are based on the optical characteristic of the smoke (De Vries and Kemp, 1994), while others are based on the smoke motion (see Figure 2). It should be noted that smoke detection is very difficult in many environments due to clouds, poor illumination, and low visibility conditions.

Smoke plume detection using colour cameras is achieved by comparing two subsequent images acquired by the cameras. The segmentation of the

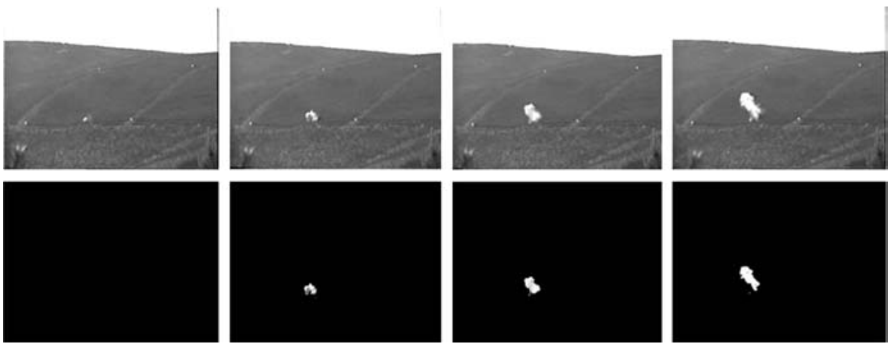

Figure 2. Temporal sequence of images for smoke segmentation.

smoke is based on differences in colour rather than light intensity, in order to avoid the varying natural background illumination that could generate false alarms. However, the variation of illumination conditions and the variety of backgrounds negatively influence the detection mechanisms, making the process complex and not reliable enough. Moreover, vibrations and motions of the cameras worsen the detection conditions. Nevertheless, recent progress in real-time image processing, which consider the analysis of motion at different levels of resolution and the integration with other environmental information will likely increase the reliability of visual-based forest fire detection (Gómez-Rodríguez *et al.*, 2002).

The required image processing for hot spot infrared or visual detection can be performed in a control centre (or command post) where images acquired by the camera are transmitted, or in a local processing unit at the location of the camera. In the first case high quality images should be transmitted to guarantee the autonomous detection efficiency, which requires high bandwidth communication. The operator at the control centre can validate the alarm visually. In the second case, the information transmitted could be just the alarm, the position of the fire if the local system can compute it, and the identification of the sensor. In this case, the reliability of the detection depends on the local processing unit, which should be powerful enough to detect and validate the alarm before sending it to the control centre. In some systems when an alarm is detected, the image of the affected area is automatically transmitted to the control centre where the validation of the alarm is performed by an operator who examines the image.

Finally, it should be mentioned that new techniques such as the use of lidar and microwaves are being tested for forest fire detection. Although this is the subject of current research, some preliminary promising results have been obtained with lidar (Utkin *et al.*, 2002) and microwave radiometers (Sadovnik *et al.*, 1999; Kaiser and Kempka, 2001).

4. Airborne Systems

Airborne fire detection is often based on human surveillance from planes flown at high altitude. The crew on these planes is in charge of detecting fires or their smoke plumes. After the fire detection, if fire-fighting is on-going, these planes can be used to supervise the fire-fighting operations.

There are however several systems that are flown on board small satellites as prototypes of future automatic satellite detection systems. These systems, such as FIRES (Brieb *et al.*, 1996), acquire image in the visual, mid-infrared, and thermal infra-red spectra. They include on board data processing and fire detection algorithms that use mid-infrared channels for fire detection and thermal channels for the discrimination of false alarms. The fire detection systems are coupled with Global Positioning Systems to provide an accurate location of the detected fires, and integrated into image processing systems that provide input to the a Decision Support System operated at the central command centre.

However, most of the research on remote sensing of forest fires is in the area of satellite remote systems. Satellite systems, when compared their airborne counterparts, present several advantages, including lower data costs, and a higher data acquisition frequency.

5. Satellite Systems

Satellite systems are by far the most developed fire remote sensing devices. However, none of them is used by operational services for early fire detection. They were developed, as other remote sensing applications, because of the advantage that satellite remote sensing provides to survey large areas at very low cost. In fact, for extensive sparsely populated areas, satellite remote sensing is the only economically feasible method for fire surveillance.

Since many of the satellite sensors provide information on the infrared region of the spectrum, they are suitable for fire detection applications. It is not the intention of this article to describe all of them, mainly because none of these systems has been used by operational services in fire emergency management, and also because their accuracy in detecting fires has seldom been assessed.

The most widely used sensor for fire detection is the Advanced Very High Resolution Radiometer (AVHRR) flown on the NOAA Polar Orbiting Environmental Satellites which acquires information in five bands five bands in the green, red, mid-infrared and thermal (two) part of the spectrum. The AVHRR, which was originally intended only as a meteorological satellite, has been extensively used for many other environmental applications, including active fire detection and burnt area mapping. The fire detection algorithms used on AVHRR data follow the general guidelines for fire detection in the mid-infrared and thermal channels. The other bands are used mainly for cloud masking and discrimination of false alarms. The ability of a satellite sensor to detect a fire depends, as mentioned before, on the size and intensity of the fire. For instance, at normal environmental temperatures, a fire of 100 m^2 would need to burn at 1000 K to be detectable by the NOAA AVHRR sensor, while a fire burning at 800 K would need to occupy 400 m^2 to be detectable (Kennedy *et al.*, 1994). Both threshold and contextual methods were used for fire detection from AVHRR imagery (Arino *et al.*, 1993; Arino and Melinotte, 1995; Stroppianna *et al.*, 2000; Dwyer *et al.*, 2000). A description of existing algorithms and the comparison of their performance can be found in Giglio *et al.* (1999). The fire detection algorithms were in some cases coupled with burnt area mapping algorithms to produce a sequence of location and damage associated to a fire event (Li *et al.*, 2000). The ability of AVHRR to detect fires was also used for monitoring the fire front of very large fires (Chuvieco and Martin, 1994). In addition to fire detection algorithms, smoke detection algorithms based on neural network classification approaches were also applied with success to AVHRR imagery (Li *et al.*, 2001). Figure 3a and b shows how fires are observed by the EOS-MODIS and AVHRR sensors respectively; the first with a spatial resolution of 250 m, and the second with a spatial resolution of 1.1 km.

A geostationary satellite that has been extensively used in fire applications is NOAA GOES (Geostationary Operational Environmental Satellite). The GOES satellite acquires images every 15–30 min, at up to 1 km resolution in visible spectrum, for the detection of smoke, and 4 km resolution in thermal infrared spectrum to detect directly the heat of fires. The GOES has been systematically used to monitor forest fire activity at large scales, but not used as a fire detection device by operational services. The GOES 3.9 and 10.7 μm bands correspond to the mid-infrared and thermal regions of the electromagnetic spectrum. The GOES ABBA fire detection algorithm (Prins and Menzel, 1992, 1994) is a contextual multi-spectral thresholding method that uses dynamic local thresholds derived from the GOES satellite imagery and ancillary databases to locate fire pixels. It also provides the fire location, and estimates of fire size and temperature. In addition to direct fire detection, algorithms for smoke detection from GOES images are also available and operate routinely. The GOES Automated Smoke/Aerosol Detection Algorithm (ASADA) utilises a multi-threshold methodology using the 3.9, 10.7 μm, and 12 μm bands to map smoke and other aerosols. As described by Prins and Menzel (1996), the ASADA is based on single and multi-band difference thresholds using contextual information and a series of solar and satellite viewing parameters to distinguish smoke/haze from clouds.

The DMSP OLS (US Air Force Defence Meteorological Satellite Programme – Operational Line-scan System) and the ESA ATSR (Along Track Scanning Radiometer) have been used to derive night time fire products. The

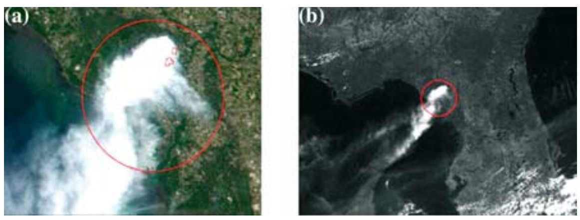

Figure 3. Observation of fires in Florida (U.S.A.) from the MODIS (a) and the AVHRR (b) sensors (courtesy of the NASA Earth Observatory).

OLS is provided with thermal and visible bands able to detect fires. However, given the long wavelength of its thermal band (10–12 μm) fires are often not detected on this range, but on the visible range (Elvidge *et al.,* 2001). The detection of the ATSR sensor relies on the use of thermal and mid-infrared bands, similar to those of the AVHRR. The NASA Tropical Rainforest Measuring Mission – Visible and Infrared Scanner (TRMM VIRS) has also been used for global active fire detections. Finally, one system that should be mentioned is the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on board the NASA EOS satellites, which provides improved spatial resolution with respect to the AVHRR and improved spectral channels that may eliminate some of the limitations of the existing sensors. The MODIS Terra and Aqua instruments allow fire detection and feed the Land Rapid Response System, which provides near real-time fire imagery. However, although the potential exists (Kaufman *et al.,* 1998), the results from this system are still to be validated. For a comprehensive description of MODIS fire products, please refer to Justice *et al.,* (2002). An interesting comparison of the suitability of some of the above sensors (AVHRR, MODIS, DMSP-OLS) for fire detection was carried out by Cahoon *et al.* (2000). They found in their study that the minimum size for a detectable fire was approximately 213 m^2 for MODIS, 435 m^2 for AVHRR, and 45 m^2 for DMSP-OLS, for a nominal fire front temperature of 1000 K and a background temperature of 305 K.

From an operational point of view, the most promising fire detection system is the FUEGO (INSA, 2000). FUEGO has been conceived as a constellation of low Earth-orbiting satellites that will survey selected regions of the Earth which are considered at risk of fires. Each satellite will have a payload including a sensor that will acquire information in the MIR region of the spectrum, in addition to dedicated thermal sensors designed especially for the detection of fires. If this mission succeeds, it will be the first one specifically dedicated to fire detection. As it stands now, in the prototyping phase of the mission, the full constellation will be made up of 12 satellites which will provide an average re-visit time of 15 min for any area on Earth. The sensor on board FUEGO will have two different modes: a fire detection mode, with limited spatial resolution, and a monitoring mode with a ground spatial resolution of 35 m. This monitoring mode will be used to follow up the evolution of the fire front, once the fire has been detected, which will help coordinate and improve the fire-fighting operations. Another innovative initiative is that of the DLR (German Aerospace Agency), which participates in the development of new satellites and sensors for fire detection. The Bispectral Infra-Red Detection (BIRD) and the FOCUS missions have the objective of testing a new generation of infrared array sensors adapted to Earth remote sensing objectives by means of small satellites. BIRD, which was launched in October 2001, incorporates thematic on-board data\processing through a neural network classifier, and real-time discrimination between smoke and water clouds. The FOCUS sensor, based on the same principles as the BIRD, is scheduled to be mounted on the International Space Station (ISS).

From the global fire monitoring perspective, the Advanced Along Track Scanning Radiometer (AATSR) instrument has been successfully launched on board the ENVISAT spacecraft on 1st March 2002, and will continue the series of fire detection products derived from the ATSR. Also, the next Visible Infrared Imaging Radiometer Suite (VIIRS) will extend the series of measurements initiated by the Moderate Resolution Imaging Spectroradiometer (MODIS) which is currently flying on EOS Terra and Aqua satellites. VIIRS is an evolved form of the MODIS sensor that utilises more bands and refined algorithms achieving improved imaging and data collection capabilities.

6. Conclusions and Discussion on the Applicability of Remote Sensing for Fire Detection

The operational detection of forest fires still relies on traditional mechanisms. According to the analysis made in the preparation of the already mentioned FUEGO programme, the distribution of fires detected by the various existing mechanisms was:

- Fixed towers 60%
- Mobile observers 30%
- Light planes 1%
- Citizen's alarms 9% (in some countries it is reported to be up to 40%)

As shown in this article, remote sensing capabilities for fire detection exist. Remote sensors (e.g. BOSQUE) have been implemented and are operationally used in ground systems for the detection of fires or smoke plumes. They complement the human visual detection available in most of the ground fire watch towers, as operational fire detection still relies on human surveillance.

Aerial systems also still rely on human visual observation for fire detection. In addition, some aerial systems incorporate, on a research basis, automatic fire detection sensors, which once tested and calibrated, may be put on-board small satellites. In some cases, infrared sensors are mounted on board aircrafts to provide indications of where smouldering fires exist, or to indicate the best points on the fire front to drop fire-retardant loads.

In the field of satellite systems for early fire detection there is still a gap between research and operation. Few examples exist in which satellite systems are integrated into operational fire detection and alert systems. One of these examples is the so-called *FireAlarm* system (Kelha *et al.,* 2001). This is a satellite-based real-time observation and alert system for forest fire management. The system, which is based on the combined use of the AVHRR and ATSR sensors onboard of the NOAA and ERS satellites respectively, works operationally in Finland. It is stable, reliable, and sends alerts when fire detection occurs. The *FireAlarm* permits the coverage of a very large region at a relative low-cost, with a false alarm rate of 10%, and enables airborne surveys to be directed to critical areas. However, its main drawback is the 3.7 h revisit time and the 1.1 km spatial resolution of the sensors, which results in detection of fires larger than 1 ha, on average. Nonetheless, *FireAlarm* is an example of how new technology can be incorporated into operational systems for improved forest fire monitoring. There are other systems that, although not used for early fire detection, provide value information on active fires and smoke. For instance, the Canadian Fire Mapping Modelling and Monitoring System (Fire M3) uses infrared imagery from NOAA AVHRR for daily monitoring of active fires and smoke across Canada. This information is further used to derive estimations of fire impact and fuel consumption on a national scale.

As sensors for fire detection and monitoring improve, and telecommunication and computer systems advance, the capabilities to ingest, process and transmit large amounts of data in real-time are becoming a reality. Also, the development of algorithms for fire detection and monitoring is fairly advanced, which brings automatic fire surveillance from satellites closer to being realised. It is only required that future satellite missions, including those especially dedicated to fire monitoring, provide data with enough frequency to minimise the re-visit time to fire risk areas.

As far as ground-based automatic detection systems are concerned, several commercial systems are currently operational with good results, although some drawbacks still exist. For instance, high resolution mid infrared detectors require cryogenic cooling systems, which increase considerably their manufacturing and maintenance cost. However, the evolution of infrared technology tends to decrease the cost and maintenance requirements of cameras that provide enough resolution for many applications.

The visual cameras used in smoke plume detection systems, on the other hand, have a lower cost than that of the mid infrared cameras. They can detect smoke even when the fire starts in the duff or shrubs below trees, or is hidden by the topography. However, smoke cannot be detected during the night. A possible solution to detect night fires with these systems is the use of additional sensors such as glow detectors. However, the image processing requirements for smoke plume detection are more complex than those of the infrared sensors. New and more reliable image processing techniques are required to detect the smoke in all varying environmental conditions. Finally, it should be noted that the integration of visual and infrared detection can provide very reliable fire detection systems. These systems would also provide more accurate fire location that will help the initial attack.

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