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AN OVERVIEW OF ACTIVE FIRE DETECTION AND MONITORING USING METEOROLOGICAL SATELLITES

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1. INTRODUCTION

Each year millions of acres of boreal and temperate forests and grasslands are consumed by wildfire resulting in loss of life and property with significant economic costs and environmental impacts. The 2000 fire season in the USA was the worst in nearly 50 years with over 8.4 million acres burned. The estimated cost of fire suppression alone was $1.3 billion. The cost of fire management and suppression is expected to increase, especially along the urban/wildland interface.

Throughout the world, fire also serves as a tool in deforestation, land clearing, grassland management, pest control, and other agricultural applications. Current estimates suggest that globally over 85% of all fires occur in the equatorial and subtropical regions primarily in Africa, South America, and Southeast Asia. Much of this activity is concentrated in developing countries where there are few resources to adequately document the extent of burning.

Biomass burning associated with naturally occurring forest fires, deforestation and other human activities is a distinct biogeochemical process that plays an important role in terrestrial ecosystem processes and regional and global climate change. Fire is a major source of trace gases such as NO, CO_2, CO, O_3, NO_x, N_2O, NH_3, SO_2, CH_3, and other nonmethane hydrocarbons. Preliminary global estimates indicate that biomass burning may be responsible for 38% of ozone in the troposphere, 32% of global carbon monoxide, 39% of the particulate organic carbon, and up to 40% of CO_2. Fire is also a significant source of aerosols (Crutzen et al., 1985; Andreae et al., 1988; Crutzen and Andreae, 1990; Levine, 1991). Studies have shown that the direct and indirect radiative effects of aerosols from biomass burning are a major factor in climate change calculations (Penner et al., 1992). Nationally and within the Framework Convention on Climate Change (FCCC), countries will need to report on their greenhouse gas emissions including those from biomass burning (Justice and Korontzi, 2001). In many countries, remote sensing may be the only economically feasible way to track fire activity.

Over the past twenty years the international scientific research and environmental monitoring communities have recognized the vital role environmental satellites can play in detecting and monitoring active fires both regionally and around the world for hazards applications and to better understand the extent and impact of biomass burning on the global environment. Although the current suite of international polar orbiting and geostationary satellites do not meet all of the needs of the hazards and climate change community, routine generation of real-time fire products would be extremely valuable to both user communities. At the present time, consistent routine global fire products are not available in real time.

Remote sensing of biomass burning is currently the focus of two international efforts that bring together remotes sensing data providers and user communities, including climate change research scientists, resource managers, fire managers, and policy and decision makers. Although the primary focus of each effort is different, they both are dedicated to better utilization of environmental satellite data to detect and monitor active fires regionally and on a global scale. The Global Observation of Forest Cover (GOFC) is a coordinated effort that was originally developed as a pilot project by the Committee on Earth Observation Satellites (CEOS) as part of the Integrated Observing strategy (IGOS), and is now a panel of the Global Terrestrial Observing System (GTOS). Forest fire monitoring and mapping is one of three primary GOFC themes. The fire hazard team of the Disaster Management and Support Group (DMSG) is an ad hoc working group of CEOS focusing on current capabilities and requirements for space-based observations for fire management applications regionally and around the world. Both groups have stated the importance of utilizing operational meteorological satellites for routine fire products and long-term analyses (Dull and Lee, 2001; Gutman, et al.,2001; Justice and Korontzi, 2001).

2. OVERVIEW OF ENVIRONMENTAL SATELLITE FIRE DETECTION

Environmental satellites have been used for fire detection and monitoring for over 20 years. Some of the initial studies were performed using the National Oceanic and Atmospheric Administration (NOAA)-6

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Advanced Very High Resolution Radiometer (AVHRR) (Matson and Dozier, 1981). This work showed how the different brightness temperature responses between the shortwave infrared (SWIR at 3.74 µm) and the longwave infrared windows (LWIR at 10.8 µm) can be used to locate fires and determine estimates of sub-pixel fire size and temperature. Typically the differences between the SWIR and LWIR bands are on the order of 2 to 4 K due to reflected solar radiation, surface emissivity differences, and water vapor attenuation. Larger differences occur when one part of the pixel is substantially warmer than the rest and in regions with enhanced solar reflection. Since the early 1980s, the AVHRR has been used to monitor fires around the globe using various algorithms ranging from single band image analyses and simple channel differencing to more complex automated contextual algorithms (Muirhead and Cracknell, 1985; Kaufman et al., 1990; Setzer and Pereira, 1991; Justice and Dowty, 1994; Flasse and Ceccato, 1996; Li et al., 2001).

Other polar orbiting sensors have been identified as appropriate for global fire detection including the Advanced Very High Resolution Radiometer (AVHRR), the ERS Along Track Scanning Radiometer (ATSR), the MODerate-resolution Imaging Spectroradiometer (MODIS), the Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS), the Tropical Rainfall Measuring Mission (TRMM) Visible and Infrared Scanner (VIRS), and the ADvanced Earth Observing Satellite (ADEOS-II) Global Imager (GLI). In the mid-latitudes these instruments provide several observations of a given region each day. In the near future a suite of geostationary satellites will be available to complement the polar network by providing information on the diurnal timing, spatial distribution, and characteristics of sub-pixel fire activity around the globe. Currently geostationary active fire monitoring using the SWIR band is only feasible in the western hemisphere with the NOAA Geostationary Operational Environmental Satellites (GOES) (Prins et al, 2001). The remainder of this paper will focus on applications of geostationary data for fire detection and monitoring.

3. GOES FIRE MONITORING IN THE WESTERN HEMISPHERE

The current series of GOES satellites provide the unique opportunity to detect and monitor active fires every half hour throughout the western hemisphere. The GOES Imager has five spectral bands (see Table 1) including a broadband visible and 4 infrared bands (Menzel and Purdom, 1994). Several features of the GOES Imager are beneficial for fire monitoring. The oversampling of the instantaneous geometric field of views (IGFOV) in the east/west direction allows for increased opportunities to capture an entire fire within one field of view. The saturation temperature on the shortwave IR window band is significantly higher on GOES-8 (335K) than that on AVHRR (320K). If the saturation temperature were near 320K, over 80% of the fire pixels observed in South America would saturate the instrument. A higher saturation temperature allows for easier fire identification in regions with high background temperatures, the ability to monitor diurnal changes in fire size and intensity, and calculations of sub-pixel fire size and temperature estimates. At nadir, the minimum detectable instantaneous fire size burning at an average temperature of 750 K is 0.15ha and increases to 0.32 ha at 50°N (see figure 3 for more details) (Prins et al., 2001).

Table 1: Geostationary Operational Environmental Satellite (GOES) Characteristics

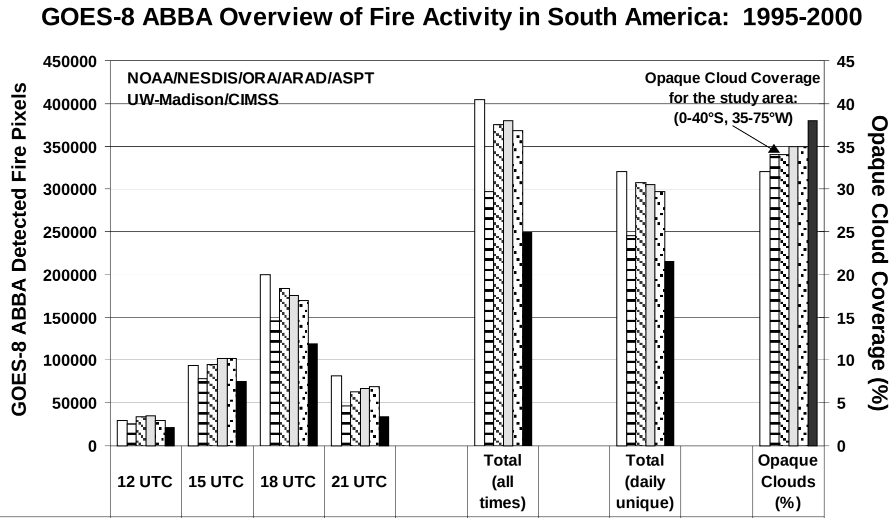
Current Systems: GOES-8 and GOES-10
Position: GOES-8 at 75 °W and GOES-10 at 135 °W
Design Life: 3-5 years
Operating Agency: National Oceanic and Atmospheric Administration (NOAA)

Band	Wavelength (µm)	Resolution IGFOV (km)	Description
VIS	0.52-0.72	1	Broadband visible
IR 3.9	3.78-4.03	4	SW-R window
IR 6.7	6.47-7.02	8	Water Vapor
IR 10.7	10.2-11.2	4	IR Window
IR 12.0	11.5-12.5	4	Dirty Window

Throughout the western hemisphere, GOES is used to detect and monitor wildfires in real time for hazard applications and to document fires associated with deforestation and agricultural management (Prins et al, 1998; 2001; Alfaro et al., 1999; Molenar et al. 2000). At the University of Hawaii and the Colorado State University Cooperative Institute for Research in the Atmosphere (CIRA) image processing techniques, such as multispectral band differencing and multi-band image combinations, are used to create derived imagery that highlight regions of possible fire activities (Weaver et al., 1995; Harris, et al. 2000). These derived composite imagery products provide a valuable tool for near real-time fire identification for the trained user. At the University of Wisconsin Cooperative Institute for Meteorological Satellite Studies (CIMSS), multispectral imagery, ancillary data, and statistical and numerical techniques are incorporated in a complex algorithm that automatically locates hot spot pixels and provides estimates of sub-pixel fire characteristics. These products are used in real time for fire identification and monitoring and fire trend analysis activities and can be assimilated into climate change and pollutant transport models in real-time (Prins, et al., 2001). The following sections provide examples of GOES fire monitoring applications being conducted at CIMSS.

3.1 GOES Biomass Burning Trend Analysis in South America

The international scientific community has stressed the need for long-term monitoring of biomass burning for land-use/land-cover change analysis and global climate change research. The NOAA/NESDIS/ORA



	12 UTC	15 UTC	18 UTC	21 UTC		Total (all times)		Total (daily unique)		Opaque Clouds (%)
□ 1995: # of Fire Pixels	29460	93681	199696	81558		404394		320652		
▤ 1996	25865	78854	145674	46291		296684		245029		
▨ 1997	33509	95247	184081	62940		375777		307069		
□ 1998	35597	102060	175435	66364		379455		305296		
▨ 1999	28781	101658	169160	68401		368000		296418		
■ 2000	21198	74723	119504	33638		249063		215218		
□ 1995: Opaque clouds (%)										32
□ 1996										34
▨ 1997										34
□ 1998										35
□ 1999										35
■ 2000										38

Figure 1. Summary of GOES-8 ABBA detected fire pixels in South America for 1995 to 2000.

Advanced Satellite Products Team (ASPT) and the Cooperative Institute for Meteorological Satellites Studies (CIMSS) developed two algorithms to monitor trends in fire, smoke, and clouds in South America using GOES-8 data. The GOES-8 Automated Biomass Burning Algorithm (ABBA) identifies and characterizes sub-pixel burning in GOES imagery (Prins and Menzel, 1994; Prins et al., 1998). It is a dynamic multispectral contextual algorithm which uses the visible, shortwave infrared window (3.9 µm) and longwave infrared window (10.7 µm) bands and ancillary data to locate fires in GOES imagery. Once a fire is found, numerical techniques are used to estimate sub-pixel fire size and temperature. The Merged Automated Cloud/Aerosol Detection Algorithm (MACADA) distinguishes smoke from various cloud types and catalogues smoke and cloud extent. The MACADA is a merged spectral/textural algorithm which uses multispectral GOES data (visible, 3.9, 10.7, 12.0 mm) to map smoke, aerosols, and clouds.

The 1995 fire season represented the first opportunity to quantitatively monitor diurnal fire activity from the GOES-8. It serves as the benchmark year in characterizing diurnal, spatial, seasonal and interannual trends in fire activity, clouds, and aerosols throughout South America. The GOES ABBA and MACADA were applied to 3-hourly (11:45, 14:45, 17:45, and 20:45 UTC) multispectral data collected from June through October in each year from 1995 to 2000. The study area extended from 0 to 40°S and from 35 to 75°W including portions of Brazil, Peru, Bolivia, Paraguay, Uruguay, and northern Argentina. Figure 1 provides an overview of the number of fire pixels detected at each time period and total burning for each year, along with the percent opaque cloud coverage. The opaque cloud coverage gives an indication if the interannual variability in the number of detected fire pixels is due to cloud coverage issues. From 1995 to 1999 the interannual differences in opaque cloud cover were less than 2% on average throughout the fire study area. Opaque cloud cover in the year 2000 was approximately 6% higher than in 1995.

The diurnal cycle is observed in all years with peak burning at 17:45 UTC. The sum of all fire pixels detected at all time periods for each year shows that 1995 was the peak year with over 400,000 fire pixels. The total number of fire pixels detected in 1996 at all time periods was 27% less than in 1995 with only a slight increase in cloud coverage. In 1997 there was increased fire activity in north-central and northeastern Brazil primarily due to drought conditions associated with El Nino, although the total number of detected fire pixels was 7% less than in 1995. In 1998 the ABBA detected elevated burning in eastern Brazil with approximately 6% less fire pixels than in 1995. In 1999 enhanced fire activity was observed in southwestern Brazil, Paraguay, and Bolivia where wildfires raged out of control, although the number of fire pixels detected was 9% less than in 1995. The 2000 fire season showed a significant decrease in fire activity, nearly 38% less than in 1995. This change was accompanied by a 6% greater occurrence of opaque clouds in the study area.

Most fires in South America can be detected from satellite for only a few hours. The daily unique column shows that on average 82% of the fire pixels observed at a given time period were not observed at the other times in a day. In the year 2000, over 86% of the fires were observed in only one of the four time periods, possibly due to cloud obscuration in other time periods. This emphasizes the importance of high temporal observing systems to capture the short-lived fires and to have more opportunities for cloud-free viewing. Comparisons with the INPE AVHRR fire product for the 1995-2000 time period show that although both instruments detect similar patterns in burning, diurnal monitoring is necessary to monitor fires as they occur (Feltz, et al., 2001).

3.2 Applications of the Wildfire ABBA Throughout the Western Hemisphere

A new version of the GOES-8 ABBA was developed for fire detection and monitoring throughout the western hemisphere. The Wildfire ABBA enables fire monitoring in most ecosystems and was streamlined to allow for rapid processing of half-hourly GOES data. GOES-8 Wildfire ABBA composite fire products are created and posted on the Web in real time at the following web site: http://cimss.ssec.wisc.edu/goes/burn/wfabba.html.
Initial evaluation of the Wildfire ABBA in Canada, Southeastern U.S., Mexico, and South America indicates improvements in identifying wildfires, distinguishing between fires and highly reflective surfaces and cloud edges, and a reduction in false alarms. In Canada preliminary studies have demonstrated the utility of high-temporal GOES data for early detection of large rapidly growing fires in remote regions of Quebec (Moreau, Personal Communication, 1999). In addition to applications in fire management, the Wildfire ABBA products are also being assimilated into the Navy Aerosol Analysis and Prediction System (NAAPS) as part of the Fire Locating and Modeling of Burning Emissions (FLAMBE) project (Prins et al., 2001).

Composites of the half-hourly Wildfire ABBA fire products provide a unique perspective regarding the prevalence and distribution of fire in the western hemisphere. Figure 2 is a composite of all fires detected in half-hourly GOES-8 imagery from 1 September 2000 through 28 February 2001. The most obvious feature of the 6-month composite is the that the vast majority of fires are located in South America, reflecting the extensive use of fire in deforestation and agricultural management. Although it is important to note that the study period did not include spring agricultural burning in Central America and the Southeast U.S.

Several areas of enhanced fire activity are outlined in North America. Clusters of fire pixels were detected in the plains of central Canada and North Dakota (location a). These fires were located in both cropland and forested regions. Although the major conflagrations in the western U.S. occurred in August of 2000, this composite shows wildfires burning in the western U.S. (location b) beyond August. Numerous fire pixels are identified along the Mississippi Delta region (location c) and are predominantly associated with agricultural activity. Fires in the southeastern U.S. (location d) are located in both cropland and forested areas. We have not been able to verify the cluster of fires in southern Florida (location e), but smoke plumes were observed in this region on a number of occasions. The fire pixels in Cuba (location f) and Central America (location g) are probably associated with agricultural burning.

The fires in the northwestern portion of South America, in the countries of Venezuela and Colombia (location h), are predominantly located in cattle ranching regions, although crops are grown here as well. Some of this fire activity is also located in forested regions. Numerous fire pixels were detected in the Guiana Highlands region of Venezuela, Guyana, and northern Brazil (location i). Thousands of fire pixels were located along the arc of deforestation in Brazil. The burning pattern is similar to what has been documented by the South American GOES-8 ABBA (Prins et al., 1998; 2001). The majority of these fires are associated with agricultural applications and deforestation activities. The composite shows distinct burning patterns along rivers and in areas with recent road construction (linear features) as observed at locations j, k, and l. The fires observed at location l represent a new region of expanding deforestation in western Amazonia associated with a new road being constructed over the Andes to link Brazil with Peruvian ports on the Pacific Coast. Fires in eastern Brazil and central Bolivia are primarily associated with ongoing agricultural management. The cluster of saturated fire pixels in south-central Argentina (location m) represents extensive fires that burned throughout December and January along the grassland/desert boundary. They produced large smoke palls that extended to the Atlantic Ocean. These fires were also observed in NOAA AVHRR imagery and were documented on the NOAA Operational Significant Events Imagery (OSEI) web site.

4. FUTURE GLOBAL GEOSTATIONARY FIRE CAPABILITIES

One of the goals of the international GOFC fire monitoring and mapping efforts is to promote and

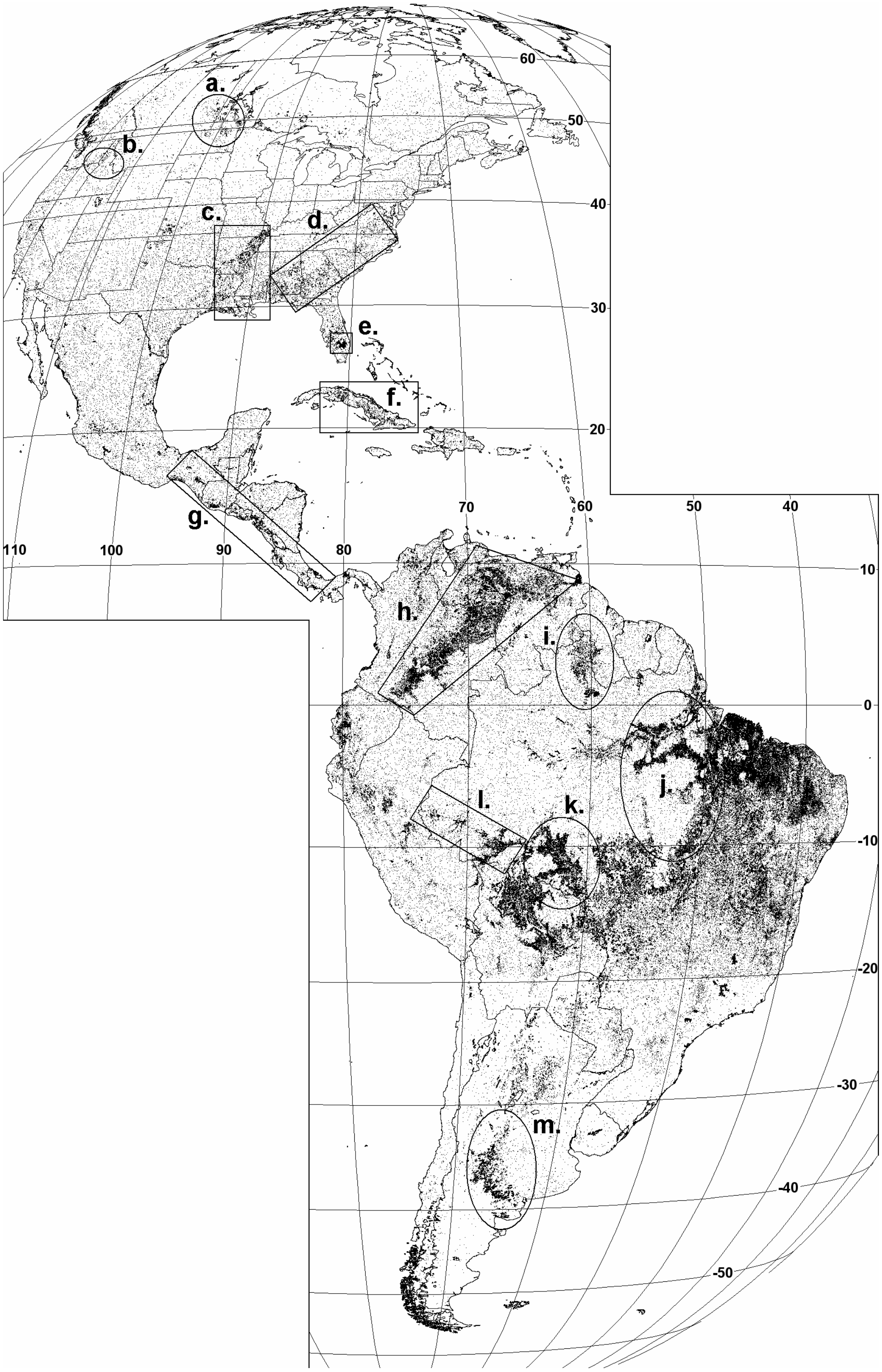


Figure 2. GOES-8 Wildfire ABBA composite of all half-hourly detected fire pixels for the time period 1 September 2000 through 28 February 2001.

support the development of a network of global geostationary satellites providing operational standard active fire products in near-real time and creating a long-term archive of fire data. A global geostationary fire network will be possible with the launch of the European Meteosat Second Generation(MSG) satellite in 2002 and the replacement Japanese Multi-functional Transport Satellite (MTSAT-1R) in 2003.

The MSG is a spin-stabilized satellite and will serve as the successor to the European Meteorological Satellite (Meteosat) series. The primary instrument on the MSG is the Spinning Enhanced Visible and Infrared Imager (SEVIRI) containing 3 visible bands (broadband centered at 0.75 µm, and bands at 0.63 and 0.81 µm), 1 near-infrared (NIR at 1.6 µm) and 8 infrared bands (3.9, 6.2, 7.3, 8.7, 9.7, 10.8, 12.0, and 13.4 µm) (see Table 2). Full disk imagery will be available every 15 minutes. The 3.9 µm band will enable sub-pixel fire monitoring in Europe and Africa with excellent coverage of the African forests. In addition, nighttime measured 1.6 µm radiance will provide quantitative observations of hot spots in the absence of reflected solar radiation contamination during the day, as demonstrated with the ATSR (Wooster and Rothery, 1997). The IGFOV at nadir will be approximately 1.6 km in the broadband visible and 4.8 km in the remaining bands, although all bands will be oversampled with a sampled resolution of 1 km in the broadband visible (HRV) and 3 km in all other bands. This oversampling can be used to enhance the spatial resolution and increases the opportunity to capture an entire fire within one field of view.

The elevated saturated temperature (>335 K) in the 3.9 µm band will minimize the impact of saturation and allow for sub-pixel fire characterization. Minimum detectable fire size estimates, presented in figure 3, indicate that MSG will be able to detect a 0.22 ha fire burning at 750 K at the equator and a 0.46 ha fire at 50°N.

MTSAT is a multi-functional three-axis stabilized satellite that is being produced by the Japan Meteorological Agency (JMA) and the Japan Civil Aviation Bureau (JCAB) to serve both a meteorological mission as the successor to the Geostationary Meteorological Satellite (GMS) series and an aeronautical mission (JMA, 1997). The initial MTSAT was lost during launch in the fall of 1999. Preliminary indications are that Japan will try to launch a replacement satellite MTSAT-1R in 2003.

The MTSAT-1R will include the Japanese Advanced Meteorological Imager (JAMI) which is similar to the GOES in terms of spectral coverage (Kigawa, 2000). This overview is based on current preliminary design specifications for the JAMI. The JAMI includes one visible band (broadband centered at 0.72 µm) and 4 infrared bands (3.75, 6.75, 10.8, and 12.0 µm). The current JAMI design specifies a spatial resolution at nadir of 0.5 km in the visible and 2 km in the infrared bands, although the data may be disseminated to the user community with the reduced resolution of 1 km in the visible and 4 km in the IR. The increased spatial resolution of MTSAT over GMS-5 and the addition of the 3.75 µm band will make geostationary diurnal fire monitoring in the western Pacific possible for the first time, with increased temporal resolution, providing coverage of the full disk region every 18 minutes.

Table 2: Meteosat Second Generation (MSG)
Launch Date: 2002
Position: Greenwich Meridian
Design Life: 7 years
Operating Agency: EUMETSAT

Band	Wavelength (µm)	Resolution IGFOV (km)	Description
HRV 0.75	0.60-0.90	1.6	Broadband visible
VIS 0.6	0.56-.71	4.8	Visible and Near IR
VIS 0.8	0.74-0.88	4.8	
IR 1.6	1.50-1.78	4.8	
IR 3.9	3.48-4.36	4.8	IR windows
IR 8.7	8.30-9.10	4.8	
IR 10.8	9.80-11.80	4.8	
IR 12.0	11.00-13.00	4.8	
IR 6.2	5.35-7.15	4.8	Water Vapor
IR 7.3	6.85-7.85	4.8	
IR 9.7	9.38-9.94	4.8	Ozone
IR 13.4	12.40-14.40	4.8	Carbon Dioxide

Table 3. Multi-functional Transport Satellite (MTSAT)
Launch Date: ~2003
Position: 140°E
Design Life: 5 years
Operating Agency: Japan Meteorological Agency (JMA) and the Japan Civil Aviation Bureau (JCAB)

Band	Wavelength (µm)	Resolution IGFOV (km)	Description
VIS 0.72	0.55-0.80	0.5	Broadband visible
IR 3.7	3.5-4.0	2	SWIR window
IR 6.7	6.5-7.0	2	Water Vapor IR
IR 10.8	10.3-11.3	2	IR Window
IR 12.0	11.5-12.5	2	Dirty Window

*Japan Meteorological Agency, 1997

The MTSAT-2, which is scheduled for launch in 2004, will be similar to the imager on the original MTSAT platform with a spatial resolution of 1 km in the visible and 4 km in the infrared bands. The infrared bands will have the same spectral configuration as the JAMI with half-hourly observations available for the entire full disk region. The saturation temperature in the 3.75 µm band on both MTSAT-1R and MTSAT-2 is expected to be near 320 K which will hinder sub-pixel fire characterization due to saturation, but saturation will still be less of an issue than with the current AVHRR 1 km Local Area Coverage (LAC) data.

The JAMI offers a unique opportunity to provide early warning in the detection of smaller fires which are not detectable by other geostationary platforms. Minimum detectable fire size estimates shown in figure 3 suggest that the spectral configuration and 2

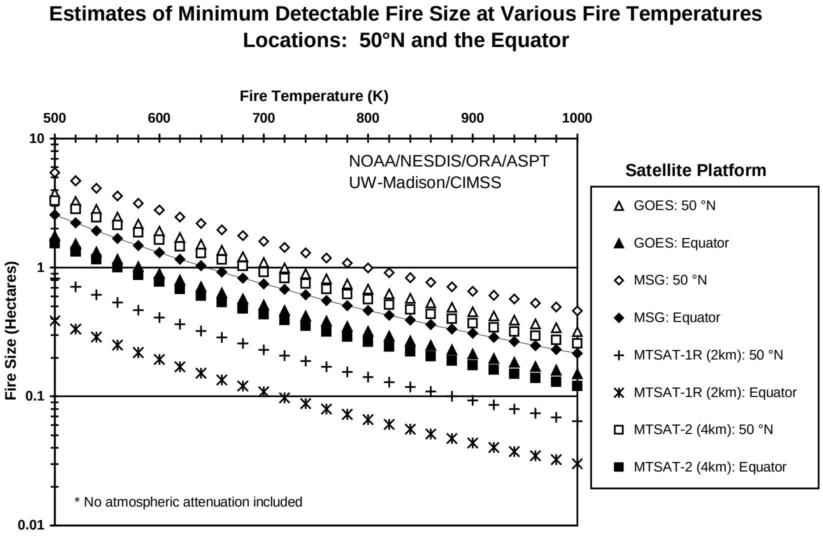


Figure 3. Minimum detectable fire size estimates for GOES, MSG, and MTSAT

km spatial resolution of the SWIR band on MTSAT-1R will allow it to detect significantly smaller fires than GOES-8. The MTSAT-1R will be able to detect a 0.03 ha fire burning at 750 K at the equator. The minimum detectable fire size at 50°N is 0.06 ha. This is 5 times smaller than the GOES minimum detectable fire size. The infrared spatial resolution of 4 km on MTSAT-2 will increase the minimum detectable fire size to 0.12 ha at the equator and 0.26 ha at 50°N for a fire burning at 750K.

5. CONCLUSIONS

Current international environmental meteorological satellites were not specifically designed for the purpose of fire monitoring and have limitations in this application. In spite of the limitations, studies have shown that they are a valuable resource for near real-time detection and monitoring of active fires. To date these satellites have been underutilized. International efforts are underway to better utilize environmental satellite data for detecting and monitoring active fires regionally and on a global scale for the wildfire management and climate change communities. In particular, operational satellites such as the NOAA POES, GOES, and DMSP platforms can provide consistent fire products from similar platforms over many years. Furthermore operational satellite data archives can be analyzed to study long-term trends in fire activity around the globe for climate applications. Within the next few years, an international suite of geostationary satellites will be able to monitor diurnal fire activity around the globe. Together with current and future meteorological/environmental polar-orbiting satellites, this suite of geostationary sensors will be able to detect and monitor fires as they occur and provide information on spatial, diurnal, seasonal, and interannual trends in biomass burning around the globe.

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