Short-Term Observations of the Temporal Development of Active Fires From Consecutive Same-Day ETM+ and ASTER Imagery in the Amazon: Implications for Active Fire Product Validation

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***Abstract*—In this study, we used same-day 30-m spatial resolution Landsat-7/ETM+ and Terra/ASTER data to study the short-term development of active fires in the Brazilian Amazon between the overpasses of the two satellites at approximately 10:00 and 10:30 local times, respectively. We analyzed the spatial progression of fire fronts and the temporal changes in the extent of burning at the scales of the pixel sizes of MODIS (1 km) and GOES Imager (4 km). The progression of fire fronts varied between individual fires, but in most cases remained within the scale of a few 30-m pixels, while the total extent of burning detected typically increased during the 30 min between the ETM+ and ASTER observations. This is in accordance with the typical mid-morning upslope part of the diurnal cycle of fire activity observed previously by coarse resolution sensors. We also assessed the potential changes in derived validation results of active fire products from medium and coarse resolution sensors. We derived fire detection probabilities from Terra/MODIS as a function of the total number of 30-m fire pixels from ASTER (representing simultaneous reference data and, hence, the "truth") and separately from ETM+ (representing nonsimultaneous reference data). We found spuriously increased detection probabilities using ETM+ resulting from the observed increase of fire activity between the ETM+ and ASTER acquisitions. While this effect can potentially be corrected for by a statistical adjustment, the overall recommendation is that a temporally unbiased sample of nonsimultaneous reference data should be used for validation.**

***Index Terms*—Fires, satellites.**

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I. Introduction

REMOTE sensing observations of active fires play an important role in a number of applications. Fire management organizations have been using near-real time active fire maps in their daily monitoring (e.g., [1]). The main advantages of active fire observations are the direct observation of the burning process; the capability to detect burning at a scale that is a small fraction of the satellite pixel; the capability to detect burning from a single satellite image; and the fast delivery time of the information [2]. Active fire data are also important to map and monitor fire dynamics from local to global spatial scales and from diurnal to interannual variability and long-term trends of fire activity [3]–[5].

Moderate and coarse resolution sensors typically provide global or near-hemispheric coverage multiple times a day. The typical temporal frequency of 1-km observations from a polar sensor is 2–4 times per day (depending on swath width and latitude), providing only a few snapshots of the fire activity at discrete times of the day. Geostationary satellites provide observations every 15–30 min, but at a coarser resolution. Neither of these systems allow for the fine scale observation of the spatial and temporal development of fire clusters. Fire spread is an important fire characteristic which has been modeled [6] and observed [7].

In this study we take advantage of a specific orbital configuration of 30-m spatial resolution sensors to observe small-scale spatial and short-term temporal development of fires. We use fire masks derived from the Enhanced Thematic Mapper (ETM+) and the Advanced Spaceborne thermal Emission and Reflection Radiometer (ASTER) on board Landsat-7 and Terra satellites, respectively. These higher spatial resolution sensors provide radiometric measurements in the shortwave-infrared spectral region that are applicable for active fire mapping [8]. The equator crossing times of Landsat-7 (10 am) and Terra (10:30 am) are 30 min apart; thus, if a fire complex is observed by both sensors on the same day, changes in the spatial position and extent within 30 min can be detected and evaluated.

Previous studies have demonstrated that for the proper evaluation of the accuracy of active fire detection products it is crucial that the thermal conditions within the entire area of the moderate resolution pixel be mapped [9]. The only viable option for a statistically robust sampling of burning conditions is the use

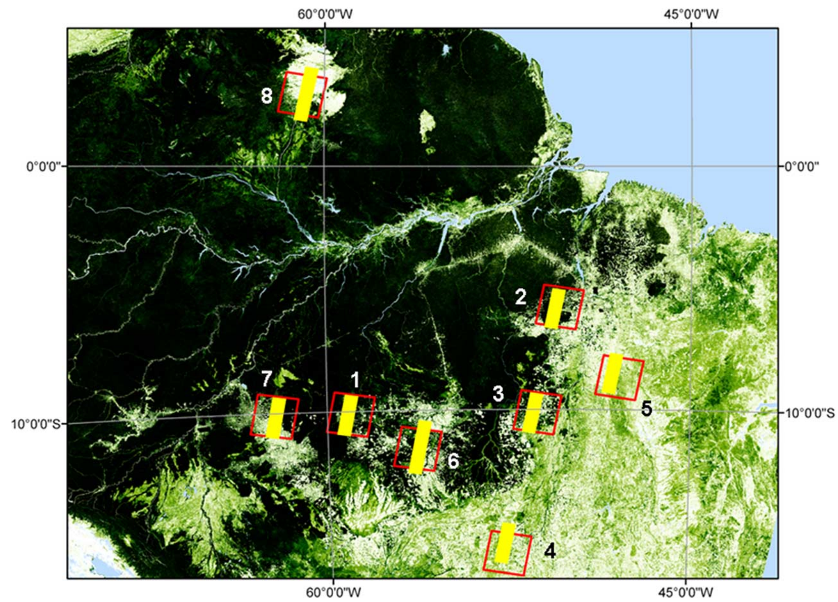

Fig. 1. Footprints of same-day ASTER/ETM+ imagery from 2001, 2002, and 2003 in the Brazilian Amazon. Dark green correspond to evergreen tropical forests whereas cerrado (savanna) vegetation predominates in light green areas on the map.

of coincident or near-coincident higher spatial resolution satellite imagery. The fire masks generated from ETM+ or ASTER are, therefore, in principle, useful for mapping the spatial extent and distribution of active fires within the pixel area of a coarse resolution sensor. This concept has been demonstrated and used for the validation of the 1-km Terra/MODIS active fire product by coincident 30-m fire observations from the ASTER sensor [10]–[12]. In the case of most coarse resolution sensors, however, there is no higher resolution sensor on the same satellite platform to provide simultaneous reference fire observations, and, therefore, the potential for the use of multiplatform configurations needs to be evaluated. The comparison of fire masks from ETM+ and ASTER imagery, therefore, also provides an opportunity to evaluate the impact of noncoincident reference data on the validation results.

II. Data

We collected a number of same-day imagery of active fires from ETM+ and ASTER over the Amazon. The identification of the available image pairs was done by first identifying ETM+ imagery with active burning from an existing database used for burned area and active fire validation and then searching for ASTER imagery on the same day and for the same WRS-2 path/row at the Land Processes Distributed Active Archive Center (LP DAAC) hosted by the United States Geological Survey (USGS) as part of the National Aeronautics and Space Administration (NASA) Earth Observing System (EOS). The data products used were Level 1G and Level 1B for ETM+ and ASTER, respectively (both radiometrically calibrated and geometrically corrected counts).

While no comprehensive search was carried out for the entire ETM+ data record, we were able to identify 8 ETM+ images in the Amazon with corresponding same-day ASTER imagery. We collected imagery of fires burning in the forest or at the forest/nonforest interface and in more sparsely vegetated areas dominated by grassland. Table I lists the ETM+/ASTER imagery, while their locations are shown in Fig. 1.

TABLE I
List of Landsat-7/ETM+ and Corresponding Same-Day Terra/ASTER Imagery as Shown in Fig. 1

Location on map	Date	WRS-2 path/row	ASTER time (UTC)	Vegetation type
1	8/13/2001	229/067	14:27:35	forest interface
			14:27:43	forest interface
			14:27:52	forest interface
2	8/29/2002	224/064	13:49:16	forest interface
			13:49:25	forest interface
			13:49:34	forest interface
3	8/29/2002	224/067	13:50:27	forest interface
			13:50:36	forest interface
			13:50:45	forest interface
4	8/29/2002	224/071	13:51:55	cerrado
			13:52:04	cerrado
			13:52:13	cerrado
5	8/31/2002	222/066	13:37:36	cerrado
			13:37:45	cerrado
			13:37:54	cerrado
6	10/5/2002	227/068	14:08:52	forest interface
			14:09:01	forest interface
			14:09:10	forest interface
			14:09:19	forest interface
7	10/17/2002	231/067	14:33:18	forest interface
			14:33:27	forest interface
			14:33:36	forest interface
8	1/28/2003	232/058	14:35:59	grassland
			14:36:08	grassland

The corresponding MODIS granules start at the beginning of the 5-minute interval (e.g. :00-:05; :05-:10 etc.) containing the ASTER data. The nominal acquisition times of the GOES-8 (East) data used in this study start at every 15 and 45 minutes after the hour.

III. Method

We generated active fire masks for the ETM+ and ASTER imagery using a contextual algorithm developed for ASTER by Giglio *et al.* [8] and adapted for ETM+ by Schroeder *et al.* [13]. This technique takes advantage of the radiative signal from

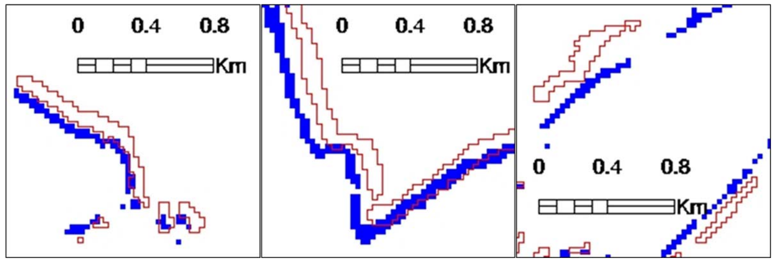

Fig. 2. Fire masks from ETM+ (solid blue) and ASTER (red contour) over segments of three fire complexes in Brazil. Left: Pasture near the forest/nonforest interface at [10.78 S, 51.38 W] (WRS-2 224/067) on August 29, 2002. Center: Cerrado (savanna) at [15.35 S, 52.55 W] (WRS-2 224/071) on August 29, 2002. Right: Grassland at [2.93 N, 60.99 E] (WRS-2 232/058) on January 28, 2003.

fires in shortwave infrared (SWIR) bands of the sensors and uses bands in the shorter wavelengths, as well as a contextual test, to eliminate false detections caused by solar reflection and hot, homogeneous surfaces. For ETM+, the primary SWIR band was band 7 (2.09-2.35 μm), while for ASTER, we used band 8 (2.295-2.365 μm).

The gain settings of ETM+ band 7 and ASTER band 8 for the imagery used in this study were "high" and "normal", respectively, corresponding to 11.1 and 10.55 $\mathrm{Wm^{-2}sr^{-1}\mu m^{-1}}$ saturation radiances [14], [15]. This suggests that, even considering the spectral differences between the two bands, the sensitivities of the two bands were compatible to the radiative signal from flaming.

To ensure the best quality of data, each fire mask was also evaluated for any possible residual detection error and for anomalous instrument behavior near or at the saturation levels of the ETM+ and ASTER bands used. As also noted by previous studies [10], ASTER images may show blooming and spikes near the most intense part of the fire front, resulting in additional spurious fire pixels adjacent to real fires. The ETM+ image on the other hand, may show pixels with near zero radiance values within clusters with the most intense radiant energy from fires, suggesting a folding of the instrument output counts at saturation. Most of these artifacts were corrected for using spectral information from additional bands in shorter wavelengths (e.g., ETM+ band 5 at 1.65 μm and ASTER band 4 at 1.7 μm). In these bands radiative signal even from the most intense fires is weaker and thus unsaturated, allowing for the delineation of the correct areas of burning. However, in the case of some of the most intense fires, the radiative signal from smoke prevented us from establishing the exact location of the fire front. Such areas were excluded from the quantitative analysis. See Section V for further discussion of this issue.

Once the fire masks were derived, the images were manually coregistered using well distinguishable surface features. This procedure yielded an estimated coregistration error of up to 1 pixel. The coregistered fire masks were overlain for visual inspection of the spatial displacement of the fire fronts. Displacement was measured in the normal direction along the fire front on the ETM+ imagery.

The fire masks from ETM+ and ASTER were mapped into the footprints of MODIS and GOES pixels. As the ETM+ and ASTER imagery are near the center of the MODIS swath (ASTER has a limited angular range around the nadir of the Terra overpass), the pixel footprints were close to the nadir nominal 1-km resolution. However, in the mapping, we accounted for the effective 2×1 km footprint of the MODIS caused by the triangular line scan function. For the GOES-8 (East) satellite used in this study, the Amazon region is also close to the sub-satellite point, and, therefore, the GOES Imager footprints were close in size to their 4-km nadir resolution.

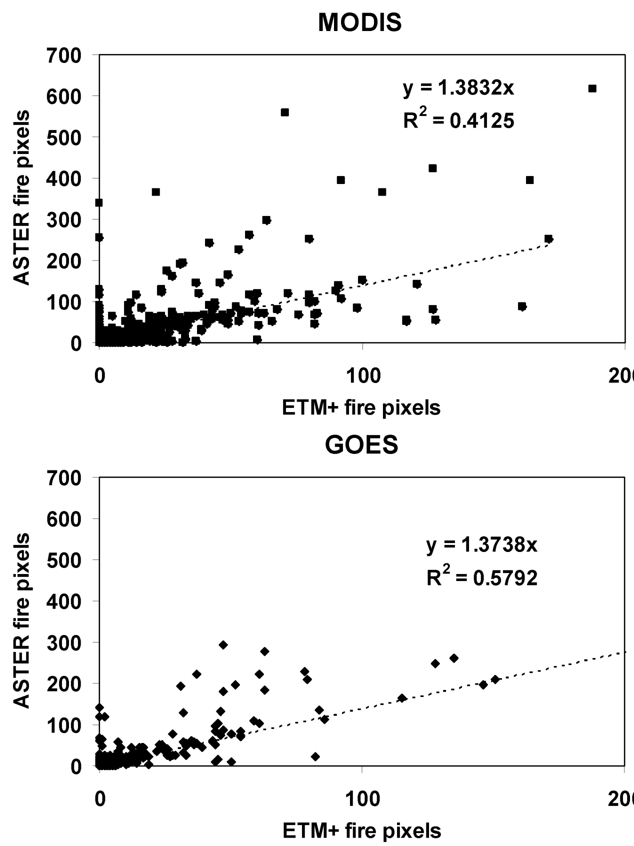

Fig. 3. Relationship between the number of ETM+ and ASTER fire pixels within MODIS (top) and GOES (bottom) pixel areas.

Once the fire counts were determined within the MODIS and GOES footprints, we analyzed their temporal change between the ETM+ and ASTER acquisition times. In order to evaluate the sensitivity of the validation results to nonsimultaneous reference data, we calculated MODIS and GOES detection probabilities based on ASTER and ETM+ fire counts respectively. The detection probabilities derived using ASTER were considered as "truth" which were then compared to ETM+-based detection probabilities to represent nonsimultaneous conditions.

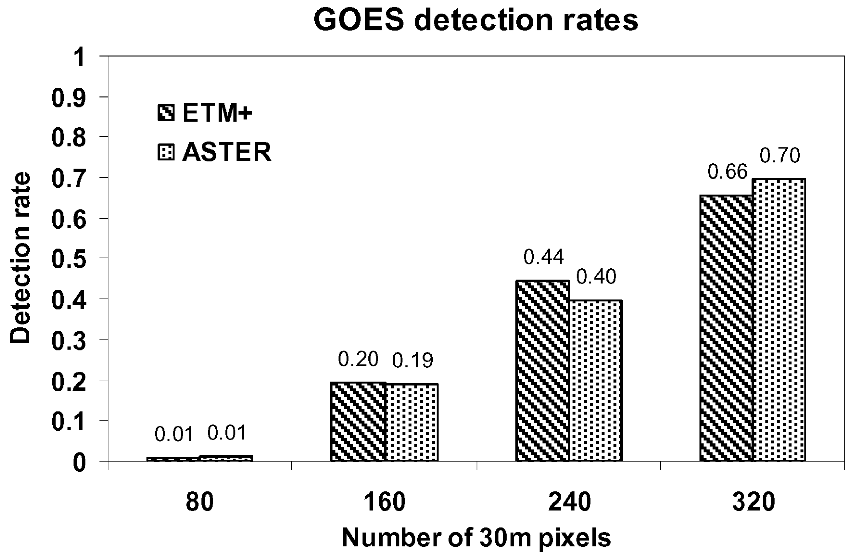

Fig. 4. Detection rates of the GOES WF-ABBA product as a function of the number of ETM+ and ASTER pixels within the GOES pixel area. Only GOES detections within ± 15 min of the ETM+ and ASTER acquisition times were considered.

IV. Results

A. Spatial Displacement

We identified a number of localized fires associated with small-scale agricultural maintenance and deforestation. These fires did not show any measurable spatial displacement. We also identified a number of fire fronts, typically in pasture, cerrado (savanna), and grassland areas, but also along the forest/nonforest interface. Spread rates were determined only for such larger fires with clearly distinguishable fire fronts. Some examples of fire fronts are shown in Fig. 2. We determined spread rates ranging between 2–6 30-m pixels within 30 min, corresponding to 120– 360 m/h. There is also a tendency for the spread rate to increase from the forest/nonforest interface towards grassland. This was a typical pattern for all fire fronts examined.

B. Changes in the Actively Burning Area

We observed an overall increase from ETM+ to ASTER of the 30-m fire counts mapped into MODIS or GOES footprints. We established statistical relationships between the ASTER and ETM+ fire counts in the form of linear regressions (Fig. 3). For all of the examples analyzed fire counts tend to increase by about 38% between ETM+ and ASTER. The lower R^2 (0.47) was found for the sample mapped into MODIS pixels. The regression is somewhat more robust for the GOES pixels ($\mathrm{R}^2 = 0.58$), which is consistent with the larger pixel area of GOES and the consequent decrease of any impact of the spatial displacement of fire fronts relative to the pixels' edges and point spread functions.

As we made substantial effort to ensure the best quality of the fire masks (see Section III), we hypothesize that this increase is primarily caused by the distinct diurnal cycle of fire activity over the Amazon, as shown by Giglio [16] using MODIS fire counts. This diurnal cycle has a marked increase in fire counts in the mid-morning, which is partly caused by the onset of new fires and partly by the growth of existing ones, which makes more fires detectable by MODIS.

V. Implications for Active Fire Product Validation

The above results can shed some light on the applicability of nonsimultaneous higher resolution fire observations for use as validation reference data of active fire products from moderate resolution sensors.

The displacement of the fire fronts, found ranging between 0–6 pixels at 30-m resolution, is small compared to the pixel sizes of moderate resolution sensors and, therefore, has a minor impact on the detection rates derived. The impact, however, is expected to be larger on the smaller MODIS pixels, which is also shown by the larger scatter of the ETM+ – ASTER fire count relationship in Fig. 3 as compared to GOES.

The change in the overall number of fire pixels, however, can result in spurious estimates of detection probabilities. To analyze this problem, we first derived GOES detection probabilities within ± 15 min of the ETM+ and ASTER acquisitions in order to further evaluate the compatibility of the 30-m fire masks from the two sensors. Note that in the case of GOES, providing observations every 30 min, both the ETM+ and the ASTER masks can be used as near-simultaneous observations within a given time window. We focused on smaller fires where the detection probabilities are rather low. The results are shown in Fig. 4. The absolute differences in the detection rates derived are rather minor, up to 4%, with no systematic bias towards either sensor. The similar detection rates for the 30-m fire reference masks from the two sensors are an indirect indication that the masks are indeed compatible.

Fig. 5 shows a comparison of Terra/MODIS detection rates derived from ETM+ and ASTER fire counts. In this case, ETM+ data are systematically collected $\sim$ 30 min before the Terra/MODIS observations, while the detection rates derived from Terra/ASTER can be considered as "truth". For a given range of 30-m fire pixel counts, ETM+ data systematically suggest higher absolute detection rates, by as much as 18%.

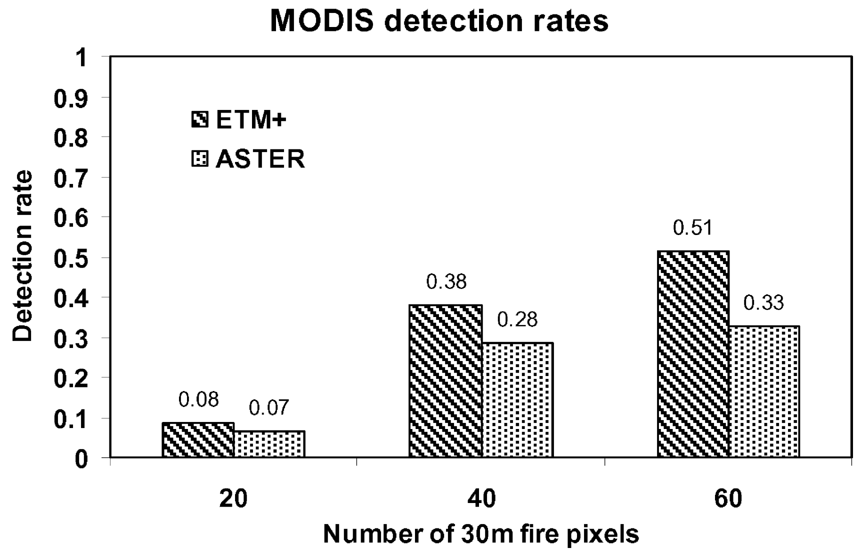

Fig. 5. Detection rates of the MODIS fire product as a function of fire counts within the pixel area from ETM+ and ASTER.

Comparing this value with the differences derived for GOES (Fig. 4), one can conclude that the differences for MODIS are indeed driven by the differences in acquisition times. As shown in Section IV-B, during the 30-min period between the ETM+ and ASTER acquisitions fires tend to grow further. Thus, any given ETM+ fire count in reality corresponds to a higher true fire count at the time of the Terra/MODIS acquisition.

VI. Discussion

The usefulness of nonsimultaneous reference observations for the validation of moderate and coarse resolution active fire products depends on the change of location and characteristics of the fire within the time period between the acquisition times. In this study we found that for the Brazilian Amazon the diurnal cycle of fire activity and the consequent change in the number and size of fires within a time period as short as 30 min results in potentially large biases in the derived detection rates if the temporal sampling is systematically biased. In the case of the ETM+ – ASTER – MODIS configuration, one possibility is to normalize the ETM+ fire counts to expected ASTER fire counts using relationships such as those derived in Section IV-B. In the absence of robust and reliable relationships that describe such temporal changes, it is necessary that the nonsimultaneous reference data are collected in such a way that they provide a statistically unbiased temporal sampling.

The acceptable time window within which reference data can be used varies by region and fire types. In the Amazon, many fires have a rather short duration and also change in intensity [13]. We recommend in that region a time window that is not larger than ± 15 min around the observations. Preliminary analysis of fires in the boreal forest of Siberia indicate less changes of the 30 min between ETM+ and ASTER and, therefore, suggests that a somewhat larger time window there might be acceptable.

In this study, we focused on the changes of location and aerial extent of fires and on the use of the latter for the validation of moderate and coarse resolution fire products. Another aspect of the problem is the change of fire radiant intensity, which also impacts detectability. Unfortunately, the ETM+ and ASTER sensors have suboptimal spectral characteristics for fire characterization [8] and, therefore, such analysis was not possible for the current study. However, future instruments, such as the planned Hyperspectral Infrared Imager (HyspIRI), one of the NASA Decadal Survey missions, will enable fire characterization at higher resolution. Similarly, airborne sensors have been emerging that provide useful reference data for fire validation [17].

The issue of fire validation using multiplatform (including aircraft and surface) configurations needs to be further explored to develop validation protocols for future satellite-based fire products, such as those from the Visible Infrared Imager Radiometer Suite (VIIRS) on board the National Polar Orbiting Environmental Satellite Series (NPOESS). Additionally, efforts need to be made to enable the validation of off-nadir fire detections, which require multiplatform data collection for even Terra/MODIS, where the ASTER data sample only near-nadir conditions. International coordination towards the use of assets operated by various agencies around the world also needs to be strengthened through programs such as Global Observation of Forest and Landcover Dynamics (GOFC-GOLD), the Committee of Earth Observation Satellites (CEOS) and the Global Earth Observation System of Systems (GEOSS).

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