Sub-Pixel Fractional Area of Wildfires from MODIS Observations: Retrieval, Validation, and Potential Applications

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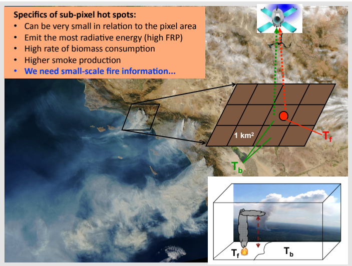
I. Introduction and Motivation

Using satellite, unmanned aircraft, and meteorological data, this study develops and validates a method to retrieve sub-pixel fire area fractions from fire pixels, detected at 1 km^2 nominal spatial resolution, by the MODerate Resolution Imaging Spectroradiometer (MODIS). A two-component model (Dozier method) for retrieving sub-pixel fire area fraction and temperature has been available since 1981. However, in the current investigation, modifications are made to the retrieval to account for atmospheric effects by implementing output from a radiative transfer model at 3.96 and 11 µm (MODIS fire detection channels). In addition, two clustering techniques are implemented to remove potential sources of error that may exist when using individual pixels. The sub-pixel retrieval will not only provide a valuable step for improving emissions estimates and plume height forecasts, but will also allow for an investigation into the meteorological effects on fire radiative power (FRP). This may prove crucial for fire weather and air quality forecasters.

Specifics of sub-pixel hot spots:
- Can be very small in relation to the pixel area
- Emit the most radiative energy (high FRP)
- High rate of biomass consumption
- Higher smoke production
- We need small-scale fire information…



MODIS Fire Radiative Power (FRP)

Advantages
- Quantitative indicator of fire intensity
- Proportional to amount of biomass consumed
- Proportional to amount of smoke released
- Related to the smoke plume height

Current FRP Limitation (collection 5)
FRP per 1 km^2

These pixels have equal FRP?

MODIS Pixel #1	MODIS Pixel #2
High fire temp.	Cooler fire temp.
Small fire area	Large fire area

We need FRP per fire area!

Fig. 1. Schematic showing the potential issues caused by sub-pixel fire characteristics for the MODIS fire detection algorithm.

II. Data & Study Region

- **MODIS** geolocation, level1B radiances, and level 2, collection 5 fire product data (1 km^2 resolution)
- **Autonomous Modular Sensor (AMS)**

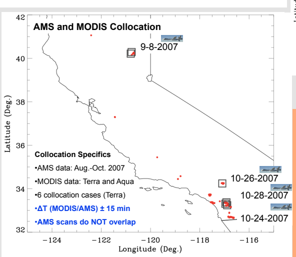


Fig. 2. Locations of the available collocations (black) and the MODIS fire pixels (red) from the various dates with AMS flights in 2007.

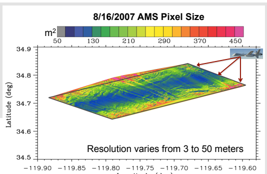


Fig. 3. Map showing the variation in AMS pixel size based on location within a single AMS flight scan.

Why obtain sub-pixel fire information?

- Improved emissions estimates
- Plume height forecasts
- Size of the fire front
- Global-scale data availability

Project Goals

- **Develop** a sub-pixel fire algorithm for MODIS
- **Validate** the retrieved data using high resolution AMS data
- **Quantify** the potential sources of error
- **Test** the retrieval on several fire events
- **Apply** the retrieval to examine the meteorological effects on fire intensity and evolution

III. MODIS Hot Spot Retrieval

The original "Dozier" method (1981), uses the spectral contrast between a sub-pixel hot target and the surrounding (presumably uniform) background of the pixel for the 4 µm middle infrared (MIR) and 11 µm thermal infrared (TIR) channels. This provides two equations that can be solved for the fire temperature (T_f) and the fractional area of the pixel covered by the fire (P). Unfortunately, the original Dozier method makes several unreasonable assumptions (Giglio and Kendall, 2001). Most significantly, all atmospheric contributions are neglected and the target (fire) and background are assumed to be blackbodies. Therefore, the approach used here is a modification of the original method and accounts for atmospheric effects by incorporating a radiative transfer model.

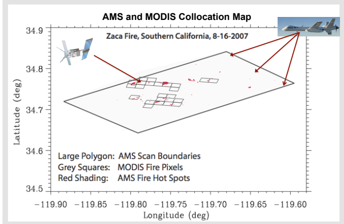


Fig. 4. An example AMS and MODIS collocation map.

The Dozier Retrieval

Calculations per MODIS pixel:

$$L_4(T) = P\,L_4(T_f) + (1-P)\,L_4(T_b)$$
$$L_{11}(T) = P\,L_{11}(T_f) + (1-P)\,L_{11}(T_b)$$

Where:
L = IR Planck Function
P = fire area fraction, where $0 < P < 1$
T_f = fire temperature
T_b = background temperature

Performing the MODIS Retrieval

LOOKUP TABLE
- SBDART Radiative Transfer Model
- Account for atmospheric effects
- Vary the potential geometries
- Vary the surface temp. (bottom of atmosphere)

MODIS INPUTS
- Geolocation data
- Level 1B radiances
- Fire product background temps.

PIXEL LEVEL RETRIEVAL

CLUSTERING RETRIEVAL
- Single Retrieval Method
- Sum Method

OUTPUTS
- **Fire area fraction**
- **Actual (surface) fire temp.**

COMPARE OUTPUT WITH AMS (Fig. 4)

IV. AMS Hot Spot Detection

Before AMS data can be used to validate MODIS retrievals, a method for AMS fire (hot spot) detection must be developed. In our algorithm, the process is automated for each MODIS pixel under scrutiny, which greatly reduces the overall complexity of the validation process. The thresholds in figure 5 are based on the unique aspects of the scatter plot or histograms within each MODIS footprint. For example, the 4 and 11 µm histograms are searched for a region of lower density above a certain minimum threshold. This region is the threshold for separating smoldering pixels from the actively burning pixels.

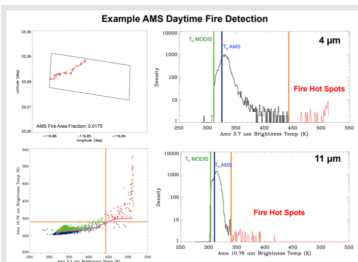


Fig. 5. AMS daytime fire detection within a MODIS pixel. (Left) Map containing the AMS hot spots within a MODIS pixel and the scatterplot of AMS 4 and 11 µm temperature with fire detection thresholds. (Right) Histograms used in AMS fire detection.

Detection Procedure (Fig. 5.)

Based on the scatter plots and histograms at 4 and 11 µm

1. Calculate AMS background temperature at 4 and 11 µm (black or blue line)
2. Ignore cold pixels (pink line and blue pixels)
3. Run fire detection on remaining data (green pixels)
4. Calculate fire detection threshold at 11 µm (horizontal orange line)
5. Calculate fire detection threshold at 4 µm (vertical orange line)
6. Remaining pixels are flagged as fire hot spots (red pixels)

V. AMS & MODIS Comparisons

Pixel Level (Fig. 6)

•The retrieval shows some skill for a fire area greater than ~0.001 km^2 (1000 m^2), which corresponds to a fire area fraction of 0.001 in a 1 km^2 MODIS pixel. Several MODIS pixel fire fractions are within 25% of the AMS fire fraction while others deviate by more than 75% (Fig. 7). These results are expected based on potential coregistration issues and other random processes (e.g. Giglio and Justice, 2003).

Cluster Level (Fig. 8)

•The sum method produces the highest correlation (R = 0.97) suggesting that the random variation can be reduced by averaging when looking at a fire event as a whole.

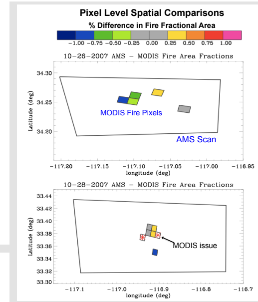


Fig. 7. Spatial comparisons of two case studies. A red asterisk indicates a pixel where the MODIS background temperature > mean pixel temperature.

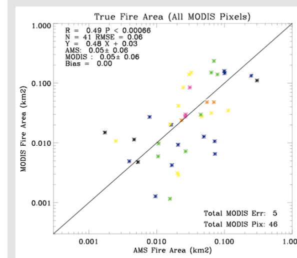


Fig. 6. Comparison between retrieved MODIS fire area (per pixel) and AMS observed fire area from six collocated cases. The color scheme indicates the variation in AMS pixel size (based on Fig. 3). Black indicates AMS mean pixel dimensions less than 10x10 meters and pink indicates AMS pixel dimensions greater than 15x15 meters within the respective 1 km^2 MODIS pixel.

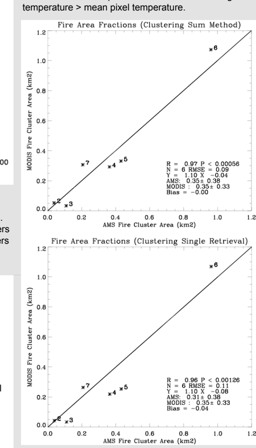


Fig. 8. Comparison between retrieved MODIS fire fractions and AMS observations using the two clustering techniques for all six collocated cases.

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