EFFECTS OF WATER VAPOUR IN RETRIEVAL OF SUBPIXEL FIRE TEMPERATURE AND FIRE AREA IN MODIS DATA

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ABSTRACT - The ability to retrieve information at subpixel spatial resolution from satellite with more than one channel in the thermal infrared spectral range had benefited the monitoring of forest fires. With better sensors, the severity of fire and the degree of damage can be estimated by retrieving fire fraction and fire temperature using Dozier procedure. Moreover, the effect of water vapour absorption is taken into account in the retrieval of subpixel fire temperature and fire area by performing a correction to remove the water vapour effect from the data before retrieval. A sensitivity analysis was also performed to estimate the uncertainty in the retrieval of fire fraction and fire temperature as a result of inaccurate determination of emissivity and background temperature.

1. INTRODUCTION

Fire hotspots have been commonly detected using the thermal bands of the AVHRR sensor on-board the NOAA satellites. The AVHRR is primarily design for the measurement of land and sea surface temperature under normal conditions. Nevertheless, it has been successfully used to monitor actively burning fires at the regional and continental scales. The low saturation levels of the AVHRR thermal bands result in fire hot spots saturating the sensor easily, causing many false alarms.

The MODIS instrument on-board the Terra satellite is equipped with infrared (IR) channels specifically designed to detect and characterise fires and their thermal energy. In comparison to AVHRR, MODIS's fire sensitive bands have higher saturation values. Hence, they are not expected to saturate except for intense wild fires covering a large area. It also uses 16 bits as opposed to 10 bits in AVHRR for signal quantization. Thus, the improved capabilities of MODIS offer an opportunity for the computation of subpixel fire temperature and fire fraction.

Dozier [1] introduced a theoretical approach to study the subpixel temperature fields using the 3.7µm and 10.6µm channels of the AVHRR. The approach was based on the assumptions that there were only two temperature fields with a "target" temperature and a "background" temperature, and that a fire pixel radiates like a blackbody. Moreover, brightness temperature is considered instead of the kinetic temperature and this is only valid provided that the emissivities are identical. From the integral of the Planck's function for different channels, the radiant temperature of one of the two temperature fields of subpixel resolution and the fraction of the pixel that each temperature field occupies can be determined.

The Dozier's procedure has been applied in NOAA AVHRR data. Using this method, Matson and Dozier [2] detected gas flares from oil fields in the Middle East and steel mills in the Midwestern United Sates. Matson and Stephens [3] applied the procedure to case studies in Mexico, Brazil, Mozambique and the Soviet Union and Flammigan [4] used this technique in his study on a forest fire monitoring system. Several problems are encountered when applying this technique in retrieving sub-pixel fire temperature and area in AVHRR data. Due to the low saturation levels of the sensor, the hotspot pixels are usually saturated, and thus equation (1) is not applicable. The thermal bands in MODIS saturate at considerably higher temperatures, and hence the hotspot pixels are usually not saturated. It is thus possible to apply this technique to retrieve the subpixel fire temperature and area.

In the thermal region, water vapour absorption is the main reason for hindering the ‘true “ radiance to be detected by the sensor. Water vapour absorption effect has then to be removed from the data before retrieval. In this paper, we report our method and results of retrieving sub-pixel fire area and temperature from MODIS data after correction for water vapour absorption.

2. METHOD

In our model, fire area is assumed to occupy a fraction *f* of the pixel area, with a fire temperature of T_f. The background forest occupies a fractional area of (1-*f)*, with a temperature of T_b. The emissivities are assumed to be the same for both the background and target areas. The detected radiance L_i of wavelength for band-i at the sensor can then be expressed as:

$$L_i = \varepsilon_i \mathrm{f} B(T_\mathrm{f}) + \varepsilon_i (1-\mathrm{f}) B(T_\mathrm{b}) \tag{1}$$

where B(T) is the Planck’s function for the radiance emitted by a blackbody at temperature T. Inversion of the Planck’s function gives the apparent temperature for band-i

$$T_i = \frac{hc}{k_B \ln\left(\frac{2hc^2}{\lambda_i^5 L_i} + 1\right)} . \tag{2}$$

If T_b and ε are known, then the two unknowns in (1) are the fractional area *f* and the fire temperature T_f. Hence if the radiance emitted by a hotspot pixel is detected at two different bands then it is possible in principle to invert the equations to solve for *f* and T_f.

Three MODIS thermal bands are used for fire detection and computation of *f* and T_f. They are bands 21 and 22, both of wavelengths (3.929-3.989µm) and band 31 (10.78-11.28µm). These channels are within the atmospheric transmission windows and have minimum water vapour and aerosol absorption. Band 22 saturates at about 335K and band 21 saturates at about 500K. T_1 is derived from band 22 whenever possible as it is less noisy and has a smaller quantization error as compared to band 21. However, when band 22 saturates or has missing data, then band 21 is used to derive T_1. T_2 is derived from band 31, which saturates at 400K. *f* and T_f cannot be determined from the two equations analytically, hence numerical method has to be employed to find the solutions.

Absolute fire hot spot detection for MODIS is based on 2 criteria [5]. If T_1>360K (330K at night) or T_1>320K (315K at night) and T_1-T_2>10K (10K at night), the pixel is then classified as a fire hot spot. All pixels of which T_1<315K (350K at night) or T_1-T_2<5K (3K at night) are immediately excluded as fire pixels. A typical value for the emissivity of vegetation (0.97) is assumed. T_b for each hotspot pixel is taken as the mean temperature computed using the radiance detected at the 10µm for cloud free pixels surrounding the hot spot. On the completion of fire hot spot detection, T_1 and T_2 are computed. Together with ε and T_b, *f* is solved numerically. With the solution of *f*, T_f can be solved.

If water vapour absorption is taken into account, equation. (1) now has an addition factor of transmittance t, as in the following expression,

$$L_i = t_i (\varepsilon_i \mathrm{f} B(T_\mathrm{f}) + \varepsilon_i (1-\mathrm{f}) B(T_\mathrm{b})) \tag{3}$$

Before performing water vapour correction, a transmittance map and a water vapour map for the dataset have to be obtained. The transmittance map is obtained by taking the ratios of the reflectance in one absorbing band with two non-absorbing bands [7],

$$T_{abs}(940\,nm) = \frac{\rho^*(940\,nm)}{C_1\rho^*(860\,nm) + C_2\rho^*(1240\,nm)} \quad (4)$$

where ρ* is the apparent reflectance, C_1 is 0.8 and C_2 is 0.2. Given the transmittance of each pixel, and Lookup Tables (LUTs) of transmission versus precipitable water for various imaging conditions generated using the MOTRAN radiative transfer code, the precipitable water for every cloud free pixel can be found. Since LUTs contain transmittance and precipitable water and they are generated for different wavelengths, the transmittance for different wavelengths is used to correct the dataset for water vapour absorption effect.

3. TEST DATA AND OBSERVATION

The subpixel fire temperature retrieval algorithm was tested using MODIS 1km resolution data acquired 14 August 2002 over Kalimantan. A total of fourteen hotspots were detected. As expected from Planck's blackbody equation, band 31 is rather insensitive to increase in fire temperature as compared to band 22. Fire temperature ranged form 493K to 811K. Fire fraction is typically rather small, ranging from 0.0021 ($2100m^2$) to 0.0167 ($16700m^2$) of a pixel. Hence the fire area would be grossly estimated if the whole pixel area was used to estimate the fire area.

Effect of water vapour is then removed from the data using the algorithm mentioned earlier before retrieving subpixel fire area and fire temperature. After water vapour correction, the fire temperatures retrieved were lower than before correction whereas fire area increases instead. Fire temperature ranged form 479K to 741K. Fire fraction remains typically rather small, ranging from 0.0025 ($2500m^2$) to 0.0476 ($476000m^2$) of a pixel. Details of the retrieved hotspots are given in Table1.

Table 1: Results of subpixel fire temperature and area retrieval

Retrieval without Water Vapour Absorption Effect Correction

Latitude	Longitude	T4	T11	T_b	*f*	T_f
-0.095	112.060	324.75	298.29	295.61	0.0129	506.42
-0.262	112.565	325.70	292.90	292.16	0.0040	614.80
-0.127	109.309	328.67	305.15	302.08	0.0167	493.33
-0.129	109.322	328.39	302.66	302.08	0.0049	589.19
-0.711	111.676	330.57	301.24	300.46	0.0048	606.32
-0.713	111.685	338.97	300.93	300.46	0.0028	713.92
-2.256	113.901	335.91	310.02	306.95	0.0149	519.66
-2.137	111.663	334.45	308.43	306.04	0.0118	533.69
-2.311	111.344	353.85	311.64	306.14	0.0159	576.99
-2.337	111.331	378.27	311.53	307.61	0.0055	811.49
-2.338	111.340	335.71	307.55	307.61	0.0028	678.62
-2.332	110.311	387.10	311.42	303.89	0.0101	752.64
-2.334	110.321	334.24	305.86	303.89	0.0090	558.05
-2.489	110.807	341.53	310.65	309.09	0.0021	755.26

Retrieval with Water Vapour Absorption Effect Correction

Latitude	Longitude	T4	T11	T_b	f	T_f
-0.095	112.060	324.78	300.48	297.78	0.0142	496.58
-0.262	112.565	325.73	294.97	294.21	0.0044	602.25
-0.127	109.309	328.71	307.91	304.79	0.0193	479.69
-0.129	109.322	328.43	305.38	304.79	0.0057	570.37
-0.711	111.676	330.61	303.45	302.67	0.0053	593.04
-0.713	111.685	339.01	303.12	302.67	0.0030	701.30
-2.256	113.901	335.95	312.31	309.18	0.0168	507.94
-2.137	111.663	334.48	310.53	308.10	0.0131	522.22
-2.311	111.344	353.88	313.72	301.36	0.0476	494.32
-2.337	111.331	378.31	313.65	305.72	0.0139	674.04
-2.338	111.340	335.74	309.58	305.72	0.0187	504.65
-2.332	110.311	387.14	313.63	306.00	0.0108	741.85
-2.334	110.321	334.28	307.99	306.00	0.0099	546.63
-2.489	110.807	341.57	312.94	311.30	0.0078	590.36

4. SENSITIVITY ANALYSIS

Since the model for the retrieval of fire temperature and fire fraction has many assumptions, it is appropriate to examine the uncertainties arise in f and T_f from inaccurate determination of various parameters in (1). Errors in the retrieval of fire temperature and fire fraction arise from sources such as errors in the determination of T_b and ε, atmospheric transmittance t and instrumental noise. Sensitivity analysis was also done by Giglio and Kendall [6] for MODIS using the analysis developed for NOAA AVHRR.

In this work, sensitivity analysis was carried out to determine how the uncertainty in the assumed emissivity (ε') and background temperature (T_b') affect the accuracy of the retrieved fire temperature and area. Hence f and T_f are functions of ε' and T_b'.

Table 2Conditions on the sensitivity test

	T_b/K	ε	f	T_f/K
Minimum	299	0.96	0.01	600
Maximum	301	0.98	0.5	1000
Step	1	0.01		

The analysis was done for several sets of ε, T_b, f and T_f given in Table2. The results show that at high T_f of 1000K and small f of 0.01 of a pixel, there is a maximum error of ±0.002 of a pixel area (±20%) in the retrieved fire fraction for a ±1K change in T_b' and ±0.01 changes in ε', independent of T_b and ε. For T_f of 600K under the same conditions, a larger error of ±0.005 (50%) of a pixel was obtained. This shows that there is greater uncertainty in the retrieval of f for small fires. This might be due to the fact that the radiance emitted by the fire being very close to the contribution from the background, hence f not being able to be resolved accurately. However, error on T_f remains at below 5% for small f. For large f of 0.5, error in f maintains at ±0.006 of a pixel area (1%) for a ±1K change in T_b' and ±0.01 changes in ε', under all cases. Error incurred in T_f is very insignificant.

Figures 1 to 8 show the uncertainties Δf and ΔT_f. for f of 0.01 and 0.5 and T_f of 600K and 1000K respectively under the same conditions. The accuracy on the retrieved fire fractional area has a direct relation with the deviation of the assumed ε from the actual value and an inverse relation with the deviation of the assumed T_b from the actual value. On the other hand, accuracy in the retrieved fire temperature is greatly determined by the accuracy in T_b.

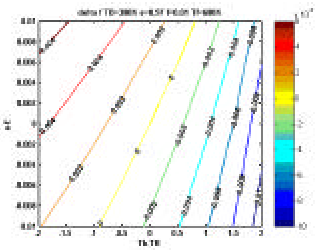

Figure 1: Plot of Δf against $\Delta\varepsilon$ and ΔT_b for f =0.01 and T_f =600K

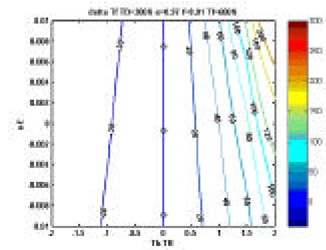

Figure 2 Plot of ΔT_f against $\Delta\varepsilon$ and ΔT_b for f =0.01 and T_f =600K

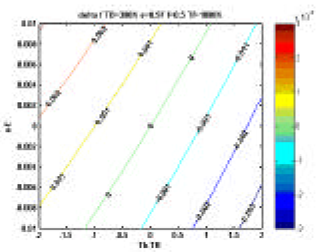

Figure 3 Plot of Δf against $\Delta\varepsilon$ and ΔT_b for f =0.01 and T_f =1000K

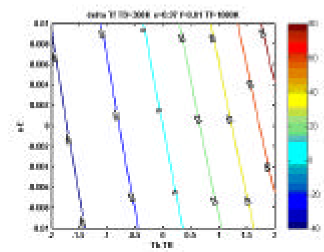

Figure 4 Plot of ΔT_f against $\Delta\varepsilon$ and ΔT_b for f =0.01 and T_f =1000K

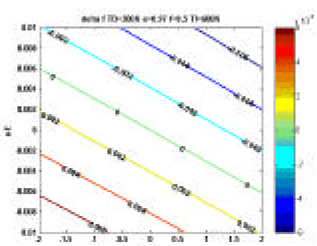

Figure 5 Plot of Δf against $\Delta\varepsilon$ and ΔT_b for f =0.5 and T_f =600K

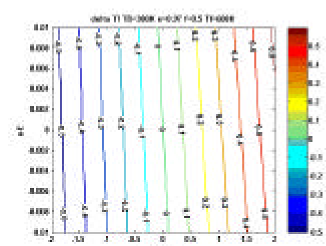

Figure 6 Plot of ΔT_f against $\Delta\varepsilon$ and ΔT_b for f =0.5 and T_f =600K

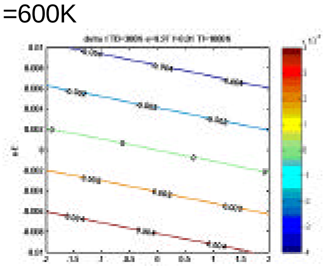

Figure 7 Plot of Δf against $\Delta\varepsilon$ and ΔT_b for f =0.5 and T_f =1000K

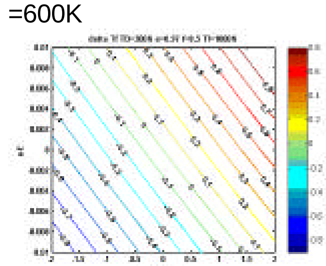

Figure 8 Plot of ΔT_f against $\Delta\varepsilon$ and ΔT_b for f =0.5 and T_f =1000K

5. CONCLUSION AND FUTURE WORK

With a higher saturation for thermal infrared channels of MODIS as compared to AVHRR, more accurate fire detection is achieved by the reduction in the number of false alarms. Fire temperature and fire fraction can also be retrieved using the Dozier algorithm. Water vapour absorption effects were also removed since in the thermal region water vapour absorption is a major influence of the measurement of "true" radiance. After correction for water vapour absorption, the retrieved fire temperature is reduced while the fire area increases by about 10%. Sensitivity analysis show that the fire temperature can be determined within an accuracy of

5% if the background temperature is uncertain within 1 K, and the emissivity is uncertain within 0.01 from the actual values. On the other hand, fire area is subject to higher uncertainty, which can be as large as 50%.

Sensitivity analysis should further encompass other parameters such as atmospheric transmittance, instrumental noise, in order to better assess the accuracy of the retrieved fire fraction and fire temperature.

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