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Wildfire temperature and land cover modeling using hyperspectral data

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Abstract

Wildfire temperature retrieval commonly uses measured radiance from a middle infrared channel and a thermal infrared channel to separate fire emitted radiance from the background emitted radiance. Emitted radiance at shorter wavelengths, including the shortwave infrared, is measurable for objects above a temperature of 500 K. The spectral shape and radiance of thermal emission within the shortwave infrared can be used to retrieve fire temperature. Airborne Visible Infrared Imaging Spectrometer (AVIRIS) data were used to estimate fire properties and background properties for the 2003 Simi Fire in Southern California, USA. A spectral library of emitted radiance endmembers corresponding to a temperature range of 500–1500 K was created using the MODTRAN radiative transfer model. A second spectral library of reflected solar radiance endmembers, corresponding to four vegetation types and two non-vegetated surfaces, was created using image spectra selected by minimum endmember average root mean square error (RMSE). The best fit combination of an emitted radiance endmember and a reflected solar radiance endmember was found for each spectrum in the AVIRIS scene. Spectra were subset to reduce the effects of variable column water vapor and smoke contamination over the fire. The best fit models were used to produce maps of fire temperature, fire fractional area, background land cover, land cover fraction, and RMSE. The highest fire temperatures were found along the fire front, and lower fire temperatures were found behind the fire front. Saturation of shortwave infrared channels limited modeling of the highest fire temperatures. Spectral similarity of land cover endmembers and smoke impacted the accuracy of modeled land cover. Sensitivity analysis of modeled fire temperatures revealed that the range of temperatures modeled within 5% of minimum RMSE was smallest between 750 and 950 K. Hyperspectral modeling of wildfire temperature and fuels has potential application for fire monitoring and modeling.

Keywords: Wildfire; Fire temperature; Radiance modeling; Airborne Visible Infrared Imaging Spectrometer (AVIRIS)

1. Introduction

Fire propagates through the combustion of fuels consisting of live and dead plant material. Fuel temperature must be high enough to volatilize and ignite these materials. Once ignition has occurred, the energy released through combustion raises the temperature of adjacent fuels. Pyne et al. (1996) links stages of combustion to temperatures at which they typically occur. As fuel temperature increases above 470 K, the volatilization of fuels begins, in a process called pyrolysis. Volatilized fuels can combust once the fuel temperature reaches 700–750 K. Flaming combustion typically occurs in wildland fuels between flame temperatures of 1070–1470 K, although maximum temperatures are believed to be as high as 2500 K. Smoldering combustion occurs at lower temperatures in denser fuels (Pyne et al., 1996).

As the temperature of the combusting fuels increases, the energy radiated by the fire increases and shifts to shorter wavelengths. By measuring thermal emission within multiple channels, remote sensing can be used to determine the dominant temperature of a fire. A temperature retrieval method developed by Dozier (1981) utilizes a middle infrared (MIR) channel and a thermal infrared (TIR) channel to separate the spectral contributions of fire and a cooler background. Planck functions for the fire thermal radiance and background thermal radiance are used to determine fire

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temperature and fire fractional area, the percent area of a fire within a pixel:

$$L_\lambda = f_{\mathrm{fire}}\beta(\lambda, T_{\mathrm{fire}}) + f_{\mathrm{background}}\beta(\lambda, T_{\mathrm{background}}) \quad (1)$$

where L_λ is the radiance at a specific wavelength λ, f_{fire} is the fire fractional area, $f_{\mathrm{background}}$ is the background fractional area, $\beta(\lambda,T)$ is a Planck function, T_{fire} is the temperature of the fire and $T_{\mathrm{background}}$ is the temperature of the background. The fire fractional area and background fractional area sum to 1. Eq. (1) exists for the spectral radiance in each channel, and for two or more channels the equations can be solved simultaneously to estimate fire temperature. Modifications of the Dozier (1981) technique have been used to retrieve fire temperature from Advanced Very High Resolution Radiometer (AVHRR) data (Matson & Holben, 1987), airborne radiometer data (Riggan et al., 2004), and Bi-spectral InfraRed Detection (BIRD) data (Oertel et al., 2004; Wooster et al., 2003; Zhukov et al., 2005). These approaches have used a small number of channels in the MIR and TIR to determine fire temperature.

The shortwave infrared (SWIR), the spectral region between 1100 and 2500 nm wavelength, can also be used for retrieving fire temperature. Unlike the MIR and TIR, the spectral contribution of background emitted radiance in the SWIR is minor. However, reflected solar radiance does make a significant contribution to the total measured radiance in the SWIR, even for hot fires. Like in the TIR and MIR, smoke has a relatively high transmittance in the SWIR. Green (1996) adapted the Dozier (1981) method to Airborne Visible Infrared Imaging Spectrometer (AVIRIS) radiance data that included the SWIR spectral region. AVIRIS collects 224 contiguous channels across an approximate spectral range of 370–2510 nm. Precise radiometric calibration of the AVIRIS instrument permits accurate quantification of at-sensor radiance (Green et al., 1998). The method proposed by Green (1996) models reflected solar radiance and two emitted blackbody radiances. The sum of these three radiances is fit to the spectral shape of the AVIRIS measured radiance using a non-linear least squares fitting routine.

This research expands on the method developed by Green (1996) for hyperspectral data. Reflected solar radiance and emitted radiance from a single source were summed and compared to AVIRIS measured radiance for a 2003 wildfire in Southern California. Radiance endmembers were used to create a linear spectral mixing model, and the best fit linear spectral mixing model was used to identify fire temperature and land cover within a fine spatial resolution AVIRIS scene. This research significantly improves the Green (1996) method by allowing multiple possible land cover endmembers. Simultaneous modeling of fire and fuel properties may allow improved modeling of fire behavior.

2. Background

The total spectral radiance measured by a sensor imaging a fire in daylight will be a combination of emitted radiance and reflected solar radiance. Atmospheric absorption and scattering of both emitted and reflected radiance (path radiance) must also be accounted for in the measured at-sensor radiance. Wavelength-specific, at-sensor radiance ($L_{\lambda t}$) can be expressed as a sum of the individual source radiances:

$$L_{\lambda \mathrm{t}} = L_{\lambda \mathrm{r}} + L_{\lambda \mathrm{Pr}} + L_{\lambda \mathrm{e}} + L_{\lambda \mathrm{Pe}} \quad (2)$$

where $L_{\lambda \mathrm{r}}$ is the reflected solar radiance, $L_{\lambda \mathrm{Pr}}$ is the reflected solar path radiance, $L_{\lambda \mathrm{e}}$ is the emitted radiance, and $L_{\lambda \mathrm{Pe}}$ is the emitted path radiance. A single emission source is assumed. $L_{\lambda \mathrm{r}}$ and $L_{\lambda \mathrm{Pr}}$ are influenced by two-way transmission through the atmosphere, accounting for both the downwelling solar irradiance and the resulting upwelling reflected solar radiance. Assuming that the emission source is on the ground, $L_{\lambda \mathrm{e}}$ and $L_{\lambda \mathrm{Pe}}$ are solely upwelling radiance terms influenced by one way path transmittance through the atmosphere.

Emitted radiance is a function of temperature, emissivity, and atmospheric absorption and scattering. The emitted spectral radiance of a blackbody can be calculated using Planck's equation:

$$L_\lambda = \frac{2hc^2}{\lambda^5\left(e^{\frac{hc}{k\lambda T}} - 1\right)} \quad (3)$$

where T is the temperature in Kelvin, λ is the wavelength, c is the speed of light, h is Planck's constant, and k is Boltzmann's constant. The wavelength of peak radiance ($\lambda_{\max}$) for a blackbody can be determined by taking the derivative of Eq. (3):

$$\lambda_{\max} = \frac{a}{T} \quad (4)$$

where a is a constant equal to 2.898×10^{-3} K m. The total radiance for a blackbody can be determined by taking the integral of Eq. (3):

$$L = \frac{2k^4\pi^4T^4}{15h^3c^2} \quad (5)$$

Eqs. (4) and (5) show that as temperature increases, the wavelength of peak radiance shifts to shorter wavelengths and the total emitted radiance increases. Table 1 lists the

Table 1
Temperature, wavelength of peak radiance ($\lambda_{\max}$), total radiance (L) and radiance within the spectral region covered by AVIRIS (L_{AVIRIS})

Temperature (K)	$\lambda_{\max}$ (μm)	L (W m^{-2} sr^{-1})	L_{AVIRIS} (W m^{-2} sr^{-1})
288	10.06	1.24×10^2	4.09×10^{-4}
300	9.66	1.46×10^2	9.45×10^{-4}
400	7.24	4.62×10^2	1.58×10^{-1}
500	5.80	1.13×10^3	3.65×10^0
600	4.82	2.34×10^3	3.12×10^1
700	4.14	4.33×10^3	1.50×10^2
800	3.62	7.39×10^3	5.06×10^2
900	3.22	1.18×10^4	1.33×10^3
1000	2.90	1.80×10^4	2.96×10^3
1100	2.63	2.64×10^4	5.81×10^3
1200	2.41	3.74×10^4	1.04×10^4
1300	2.23	5.15×10^4	1.72×10^4
1400	2.07	6.93×10^4	2.68×10^4
1500	1.93	9.14×10^4	4.00×10^4